THE PROPAGATION OF TRIPLEN HARMONICS CURRENT PRODUCED BY SYNCHRONOUS GENERATOR WHEN CONNECTED TO NON-LINEAR LOAD

By

Muhammad Afiq Bin Yusof

Final report submitted in partial fulfillment of
The requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

SEPTEMBER 2011

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CERTIFICATION OF APPROVAL

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Approved by,

(Ir Mohd Faris Bin Abdullah)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
SEPTEMBER 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD AFIQ BIN YUSOF

ABSTRACT

With the advancement in technology and the increasing growth of industrial commercial facilities, problems in power quality such as harmonics distortion have always been a major concern among engineers. This is particularly true in power system, where usage of power is very high as there are many large-scale types of equipment being used such as synchronous generator and non-linear load which have been proven to produce harmonics. Since no one has ever tested the effects of triplen harmonics produced by both of them when connected together, it would be valuably useful to monitor and simulate these problems in power quality.

The objective of this paper is to study the propagation of triplen harmonics current produce by the synchronous generator when connected to non-linear load. By doing so, we would be able to investigate, validate and improve the existing findings on triplen harmonics current cause by both synchronous generator and non-linear load.

This paper is aimed to study the propagation of triplen harmonics when synchronous generator is connected to non-linear load through researches from published journals, lab scale experiments and simulation using PSCAD software.

In this project, the research methodologies are divided into six different stages. The project activities begin with some preliminary research work. The process continues with lab scaled experiment followed by simulation modeling using PSCAD software. The data gained will then be compared so it could be used in result analysis and discussion. The final stage will be the final documentation.

By the end of this paper, hopefully this research will help people in industries to understand the cause and effects of triplen harmonics produce by both synchronous generator and non-linear load.

ACKNOWLEDGEMENT

I would like to begin by expressing my utmost gratitude to Allah s.w.t for His blessing. Without His bless, this Final Year Project will not be successful.

My deepest appreciation goes to my supervisor, Ir. Mohd Faris Bin Abdullah for his never ending support to complete my final year project. I would also like to thank him for his tirelessly supervision and encouragement in all aspects from the beginning until the final of this project.

Special thanks to my fellow colleagues, Muhammad Arif Bin Md Nor, Amnina Binti Kamaluddin and Faiz Izzat Bin Mohamed Akhir for sharing their understanding and knowledge throughout my project development. Without their willingness to give assistance, this project may not be accomplished with success.

Not to forget, I gratefully acknowledge Universiti Teknologi Petronas (UTP) particularly Electrical and Electronic Engineering Department for providing the opportunity for student to gain experience in doing research and experimentation works.

The journey of completing my final year project was full with memorable experience and it was my pleasure to work with everyone here. Last but not least, thanks to my family especially my parents and also my friends for their support.

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CHAPTER 1
INTRODUCTION

1.1 Background Study

Investigation reveals that, synchronous generating units produced triplen harmonics current that flow through the Neutral Earthing Resistor (NER) during operation causing a NER failure. Based on previous findings, non-linear load has also been proved to be most of the sources that produced triplen harmonics. So, the purpose of this paper is to study the propagation of triplen harmonics current produced by synchronous generator under non-linear load configuration. The propagation of triplen harmonics current produced by synchronous generator connected to a non-linear load can be modeled by triplen harmonics voltage acting as the source for zero sequence networks. Time domain analysis is used for simulation and the model is validated with the triplen harmonics current measured in the lab.

1.2 Problem Statement

If not properly designed or rated, electrical equipment will often malfunction when harmonics are present in an electrical system. Most people realize that harmonics have been around a long time. Since the first AC generator went online, electrical systems have experienced harmonics.

Synchronous generator has been proven as one of the sources of triplen harmonics in several researches. Triplen harmonics produced by synchronous generator can increase the neutral to earth voltage. Neutral to earth voltage (NEV) is the measurement of voltage between system neutral and earth surface. This measured voltage depends on the flowing of neutral current between neutral and earth, neutral impedance and earth impedance. As triplen harmonic currents is additive in the neutral, the neutral to earth voltage will increase when the neutral current is increased.

Triplen harmonics voltages can also cause voltage distortion. The supply has source impedance and because of this, the harmonic load currents give rise to harmonic voltage distortion on the voltage waveform. Study showed that the distorted voltage drop in the cable impedance is caused by the distorted load current drawn by non-linear loads. This distorted voltage waveform is applied to all other loads connected to the same circuit, causing harmonic currents to flow in them.

There are many findings that proved both synchronous generator and non-linear load produce triple harmonics. Since no one has ever tested the effects of triplen harmonics produced by both of them when connected together, the study of the propagation of triplen harmonics current produced by synchronous generator when connected to non-linear load must be done.

1.3 Project Objectives

The objective of this project is to

- Study the propagation of triplen harmonics current produce by the synchronous generator when connected to non-linear load
- Investigate, validate and improve the existing findings on triplen harmonic current produce by synchronous generator when connected to non-linear load

1.4 Scope of Study

The scope of study for this project consists of doing researches from published journals, lab scale experiments and simulation using PSCAD software.

Doing researches is important for better understanding on the topic regarding the theory and concept of triplen harmonics. All the data measured during the experiment will be compared with the simulation results in order to ensure that the data collected was accurate.

After the data measured had been proved to be accurate, detailed analysis is required in order to understand the characteristic and the relationship of the triplen harmonic current when synchronous generator is connected to the non-linear load.

1.5 Relevancy of Project

This project is mainly based on Power Quality studies and as an Electrical and Electronics student majored in Power Systems Engineering, conducting this project would give us a more precise data and a better understanding on the propagation of the triplen harmonics current produced by synchronous generator when connected to non-linear load which could lead to a better design with a better efficiencies in the future.

1.6 Feasibility of Project

This project will allow us to identify the impact of triplen harmonics current when synchronous generator is connected to non-linear load which in turn, would allow us to understand more about triplen harmonics when both of the devices is connected together. The whole project will involve two main phases which will be FYP1 and FYP2.

FYP1 will mainly be about understanding the fundamental theories regarding the project. Previous works and published journal papers related to this project will also be studied and compared in order to improve and perfect the research for future experiments. The experiments setup will also be prepared during FYP1. In FYP2, the task would be to complete the experiments and acquire all the data needed. The data obtained from the experiment will be compared with the simulation results. Detailed analysis will be done to understand the characteristic and the relationship of the triplen harmonic current when synchronous generator is connected to the non-linear load.

Based on the methodology and planning of the project milestones, the project will be able to be completed within the time given.

CHAPTER 2
LITERATURE REVIEW

2.1 Triplen Harmonics

Ideally, current and voltage waveform are perfect sinusoid. However, because of the increased popularity of electronic and other non-linear load, this waveform quite often becomes distorted. This deviation from a perfect sine wave to a distorted sine wave is called harmonics. Harmonics is sinusoidal component having a frequency that is an integral multiple of the fundamental frequency.

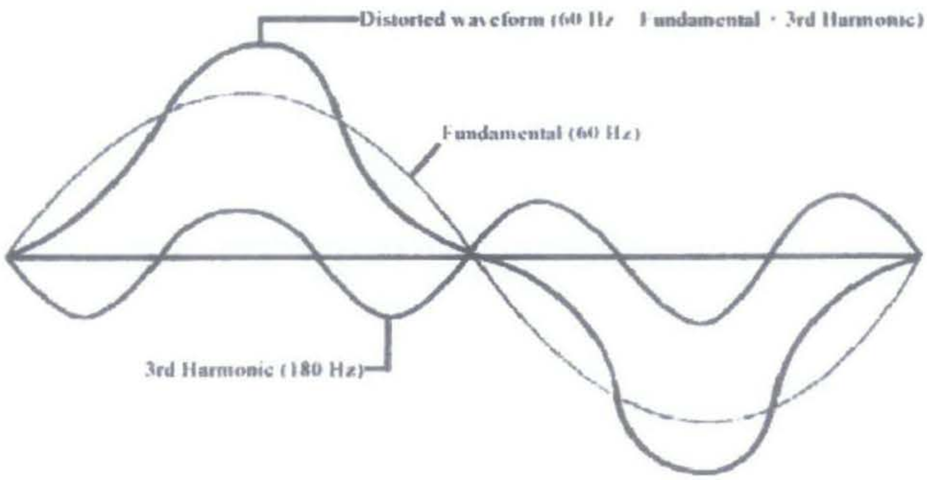


Figure 2.1: Distortion Waveform Consist Of Fundamental and Third Harmonics

Triplen harmonics currents are currents in the order of 3rd, 9th, 15th etc. Under balanced condition, triplen harmonics currents add up at the neutral. Thus, the magnitude of triplen harmonics currents at the neutral is three times the phase triplen harmonics currents [1]. Triplen harmonics currents are zero sequence harmonics currents that return to neutral.

Triplen harmonics currents will cause overload of neutral conductor or bus bars and consequently appreciable voltage drop between neutral and earth. In delta-wye step down transformer, the neutral of wye secondary winding will carry triplen harmonics currents. In respond to this, triplen harmonics currents will circulate in delta primary winding which may cause overheating and transformer failure. Wye connected power capacitors can be damaged by high triplen harmonics currents during parallel resonance [2]. In some cases, triplen harmonics currents have caused NER failure [3].

2.2 Triplen Harmonics Produced By Synchronous Generator

Naturally, synchronous generator produces triplen harmonics voltages which then drive the triplen harmonics currents. Parameters such as the pitch factor, distribution factor and the slot skew of the synchronous generator will affect the characteristics of the triplen harmonics produced. Studies on the third harmonics show that the propagation of triplen harmonics currents is adequate because a high value of triplen harmonics frequency will always be opposed by a higher value of impedance [4].

From the analysis done by [5], it was revealed that during the operation, when a synchronous generator is connected in parallel with the utility grid, the triple harmonics currents produced by the synchronous generator flow in the opposite direction of the load flow. Since underground cable capacitance and transformer winding vector groups have great influence on the propagation of triplen harmonics currents, the triplen harmonics currents will flow through the zero sequence impedance of the network.

The magnitude of harmonics voltages decrease with respect to increase in harmonics order. Likewise, triplen harmonics currents magnitude decrease with increase in harmonics frequency due to higher zero sequence inductive reactance that proportional to frequency. Therefore, third harmonic current becomes major composition of triplen harmonics currents and its magnitude is influenced by third harmonic voltage and third harmonic zero sequence impedance [6].

2.3 Non-linear Load

A linear element in a power system is a component in which the current is proportional to the voltage. In general, this means that the current wave shape will be the same as the voltage. Typical examples of linear loads include motors, heaters and incandescent lamps.

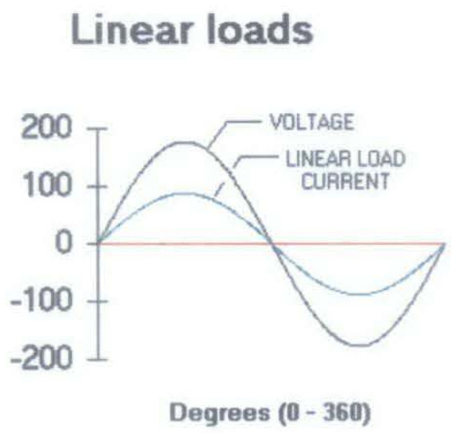


Figure 2.2: Voltage and Current Waveforms for Linear Loads

On the other hand, the current wave shape on a non-linear load is not the same as the voltage. Typical examples of non-linear loads include rectifiers, adjustable speed motor drives, ferromagnetic devices, DC motor drives and arcing equipment.

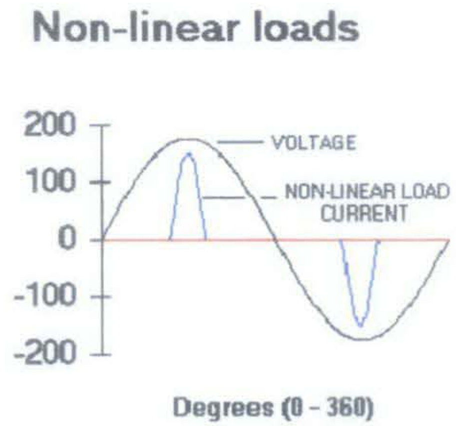


Figure 2.3: Voltage and Current Waveforms for Non-linear Loads

A load is considered as non-linear if its impedance changes with the applied voltage. The hanging impedance means that the current drawn but the non-linear load will not be sinusoidal even when it is connected to sinusoidal voltage. These non-sinusoidal current contain harmonics current that interact with the impedance of the power distribution system to create voltage distortion that can affect both the distribution system equipment and the loads connected to it.

CHAPTER 3
METHODOLOGY

3.1 Project Activities

In this project, the research methodologies are divided into six different stages. The project activities begin with some preliminary research work. The process continues with lab scaled experiment based on the identified objectives and followed by simulation modeling using PSCAD software. The data gained from the lab scaled experiment will then be compared with the data gained from PSCAD simulation in data comparison stage. Next will be the result analysis and discussion stage. The final stage will be the final documentation where everything from the beginning of stage until the last stage will be pile up together with the outcomes of the project.

3.1.1 Preliminary Research Work

This stage focusing more on data collection related to the project. It involves compilation of information gained from various journals, books and technical paper associated with the topics. Great understanding particularly in power quality, load flow and triplen harmonics current are obtained from a thorough research pertained to the project. This information will be used in conducting literature review and further stages of the project.

3.1.2 Lab Scaled Experiment

After having a great understanding particularly in harmonics, synchronous generator and non-linear load through compilation of information gained from various journals, books and technical paper, it is time to start the lab scaled experiment on triplen harmonics current produced by synchronous generator when connected to non-linear load by using a lab scaled synchronous generator and non-linear load provided in the lab. A three phase power quality analyzer will be used to measure the voltage and current produced.

The lab scaled experiment consists of single synchronous generator connected to different types of balanced load such as resistive load and inductive load where the loads value will be varied. In order to see the effect of triplen harmonics current produced by synchronous generator when connected to non-linear load, all the experiment stated above will be done by having one of the balanced load connected to the non-linear load in parallel at the line and the other one having a balanced load without connected to non-linear load.

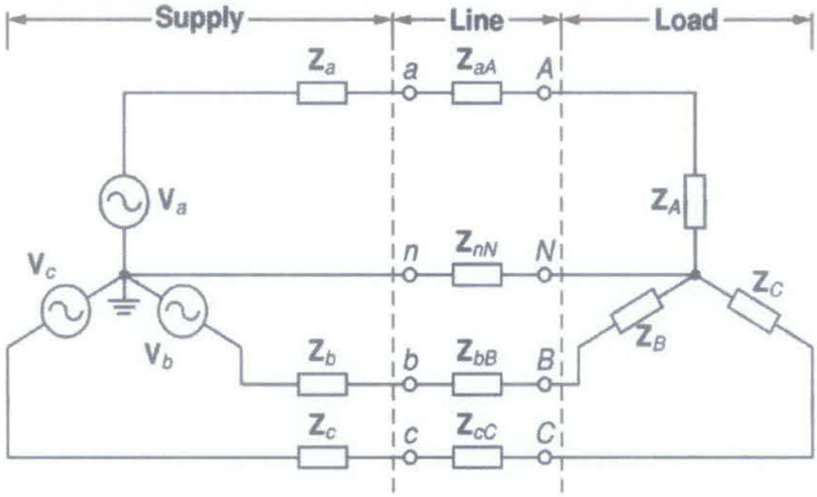


Figure 3.1: Wye – Wye Connection of Four Wires 3-Phase Circuit Diagram Used Throughout the Experiment

The lab scaled experiments that have been conducted are:

- Single Generator
  - Connected to resistive load
  - Connected to resistive load with full bridge rectifier
  - Connected to inductive load
  - Connected to inductive load with full bridge rectifier
  - Connected to resistive and inductive load
  - Connected to resistive and inductive load with full bridge rectifier

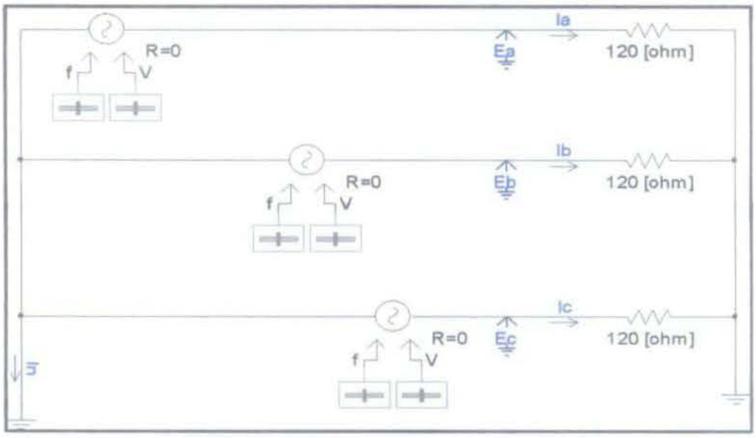


Figure 3.2: Circuit Diagram of Single Generator Connected To Resistive Load

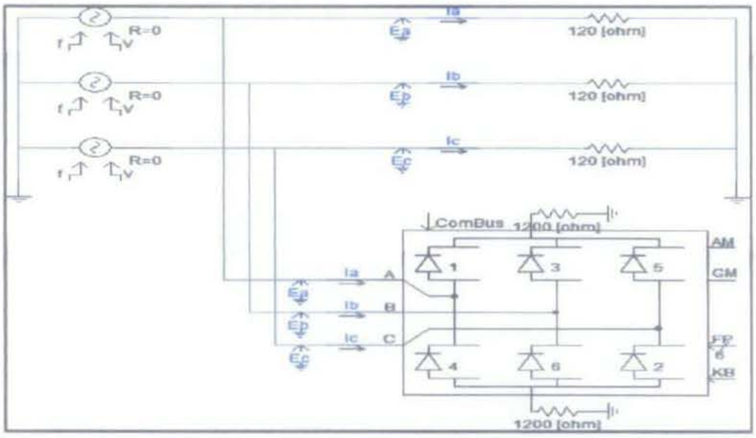


Figure 3.3: Circuit Diagram of Single Generator Connected To Resistive Load With Full Bridge Rectifier

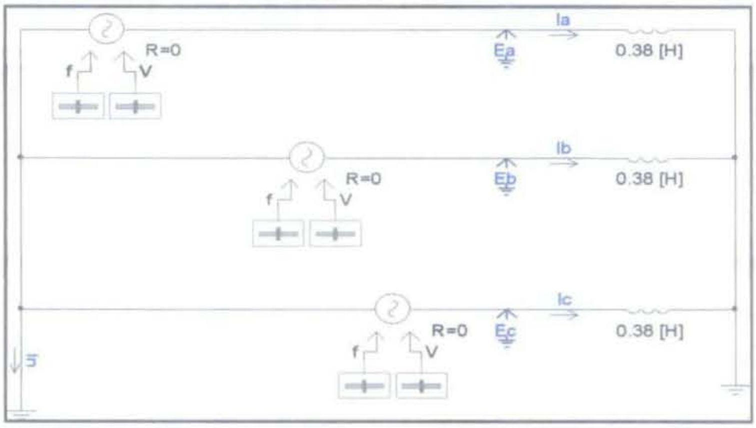


Figure 3.4: Circuit Diagram of Single Generator Connected To Inductive Load

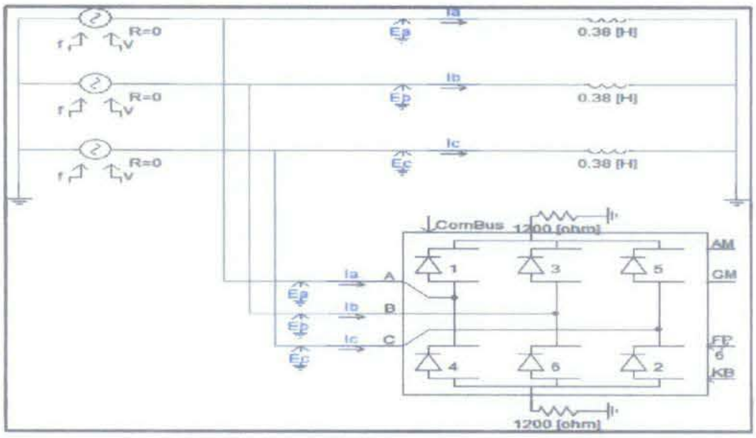


Figure 3.5: Circuit Diagram of Single Generator Connected To Inductive Load With Full Bridge Rectifier

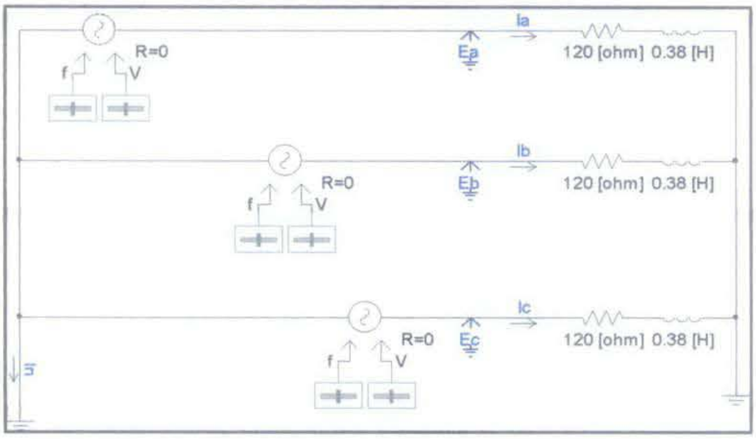


Figure 3.6: Circuit Diagram of Single Generator Connected To Resistive and Inductive Load

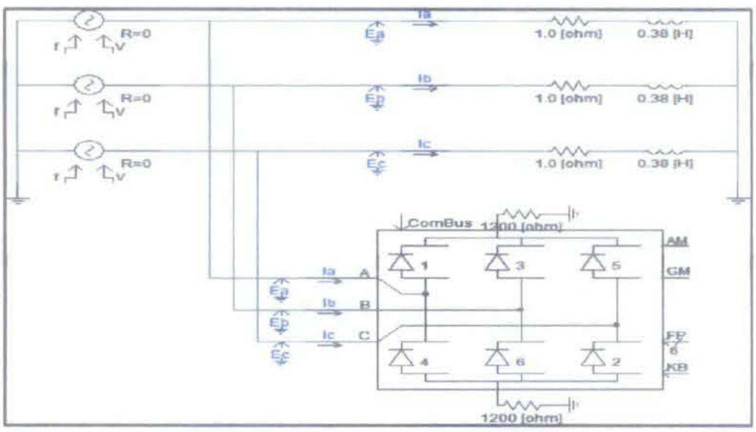


Figure 3.7: Circuit Diagram of Single Generator Connected To Resistive and Inductive Load With Full Bridge Rectifier

3.1.3 PSCAD Simulation

In order to compare the lab scaled experiment results, simulation modeling using PSCAD software need to be done. The PSCAD simulation modeling will have the same setup used in lab scaled experiment to ensure the accuracy of the results.

3.1.4 Data Comparison

After completing all the previous stages of work, the data gained from lab scaled experiment and the gained form PSCAD simulation modeling will go through some comparison and validation process. It will be compared in order to prove that the lab scaled experiments were correct and the data gained was accurate based on objectives that had been set earlier when the project is proposed. A successful data will meet all the objectives listed and capable to yield expected result in term of the propagation of the triplen harmonics current produced when connected to non-linear load. The validated data then will proceed to the next stage for result analysis and discussion.

3.1.5 Result and Discussion

During this phase, the model will be analyzed and evaluated. The result provided should meet and satisfy all the requirements of the project. Some modification for improvement could be made if necessary before entering the final stage.

3.1.6 Final Documentation

All the works related to this project will be documented in a proper manner for future use. In order to keep the individual responsible for the project on track and ensure the project to meet the necessary requirements, the documentation process will be done continuously.

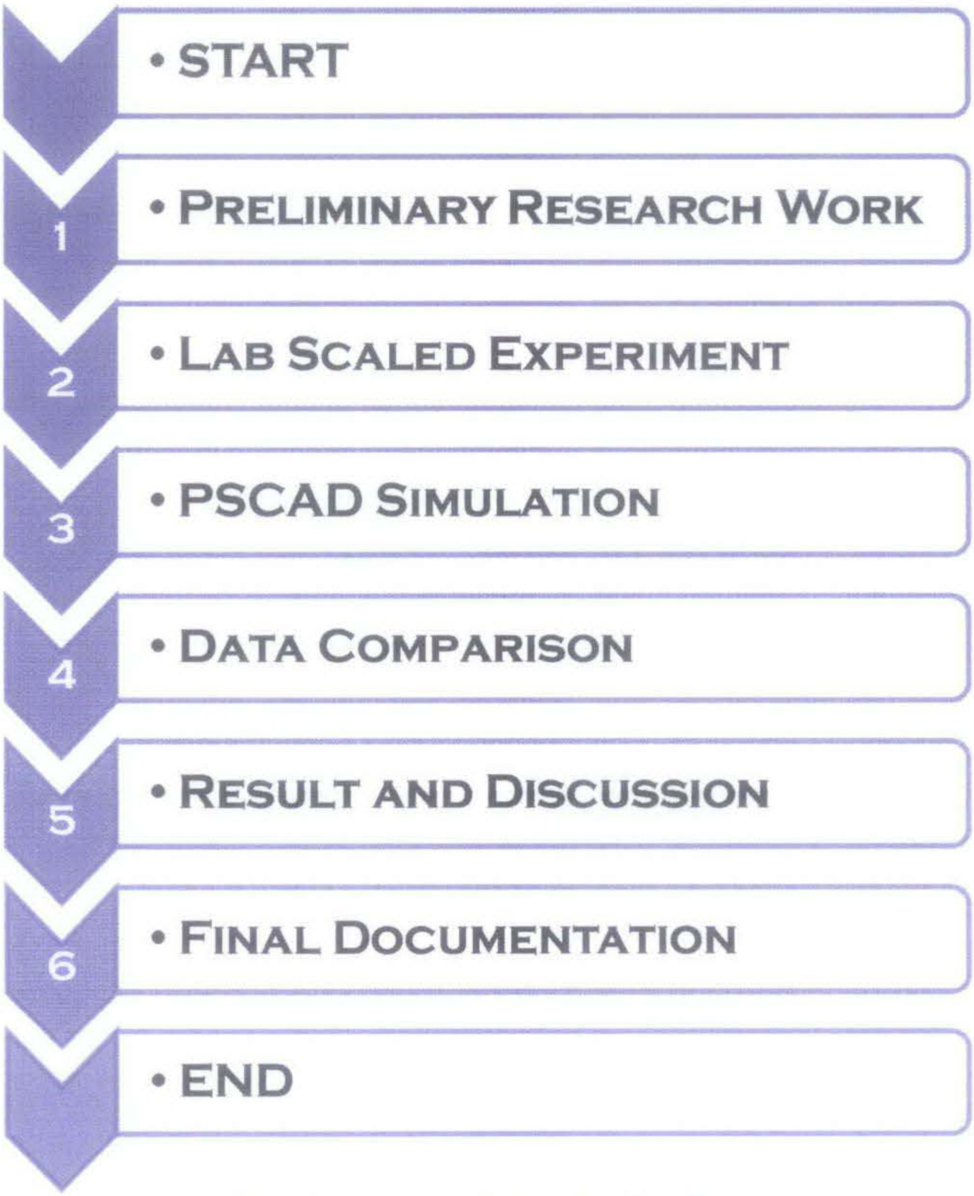


Figure 3.8: Research Methodology Flow Chart

3.2 Key Milestone

A key milestone is constructed to mark the end stage of a work or process of the project. It is an important element in order to monitor the progress and make sure that the project is on schedule. The key milestone for both first and second semesters is as shown in Table 1 below.

Table 3.1: Key Milestones for First Semester and Second Semester

FIRST SEMESTER															
No	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Completion of Preliminary Research Work														
2	Completion of Lab Scaled Experiment														
SECOND SEMESTER															
No	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
3	Completion of PSCAD Simulation														
4	Completion of Data Comparison														
5	Completion of Result and Discussion														
6	Completion of Final Documentation														

3.3 Gantt Chart

The Gantt Charts shown below describe the timeline of the project for two semesters. The schedule of the activities may change from time to time depending on the work progress.

3.3.1 Gantt Chart: First Semester

Table 3.2: Gantt chart For First Semester

No	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection and Confirmation of Project Title	●														
2	Preliminary Research Work on Related Topics		■	■	■	■										
3	Submission of Extended Proposal						●									
4	Lab Scaled Experiment							■	Mid-Semester Break	■						
5	Proposal Defense										●					
6	Lab Scaled Experiment Continues											■	■	■		
7	Submission of Interim Draft Report														●	
8	Submission of Interim Final Report															●

3.3.2 Gantt Chart: Second Semester

Table 3.3: Gantt chart For Second Semester

No	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	PSCAD Simulation								Mid-Semester Break							
2	Data Comparison															
3	Submission of Progress Report															
4	Result and Discussion															
5	Pre-EDX															
6	Submission of Draft Report															
7	Submission of Dissertation															
8	Submission of Technical Paper															
9	Oral Presentation															
10	Submission of Project Dissertation															

3.4 Tools Required

The tools required for this project can be divided into three, tools used for lab scaled experiment, tools used to measure harmonics and tools used for simulation modeling.

The tools required for the lab scaled experiment is Lab – Volt 2 kW Electromechanical Training system. It is a modular program in electric power technology. The system consists of several modules, which can be grouped to form subsystems which deal with the different techniques associated with the generation and use of electrical energy. Symbols and diagrams specific to each module are clearly silk-screened on the faceplates. Standard colorcoded safety 4 mm jacks are used to interconnect all system components. The specifications of the Lab – Volt 2kW Electromechanical Training System were attached in Appendix A.

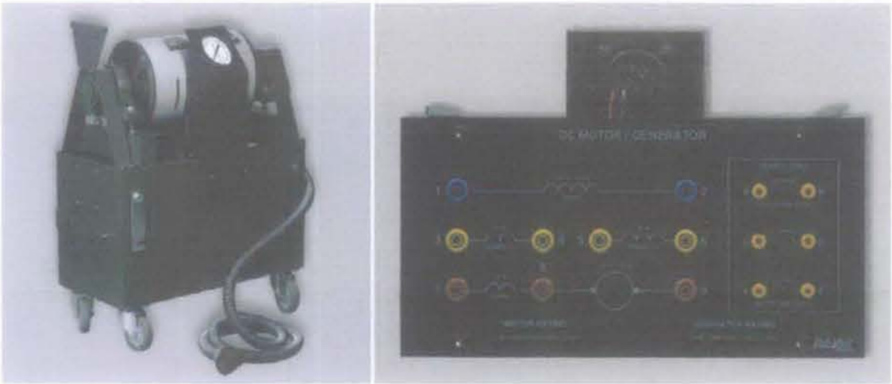


Figure 3.9: Lab Scaled DC Motor

Figure 3.10: Lab Scaled Three Phase Synchronous Generator

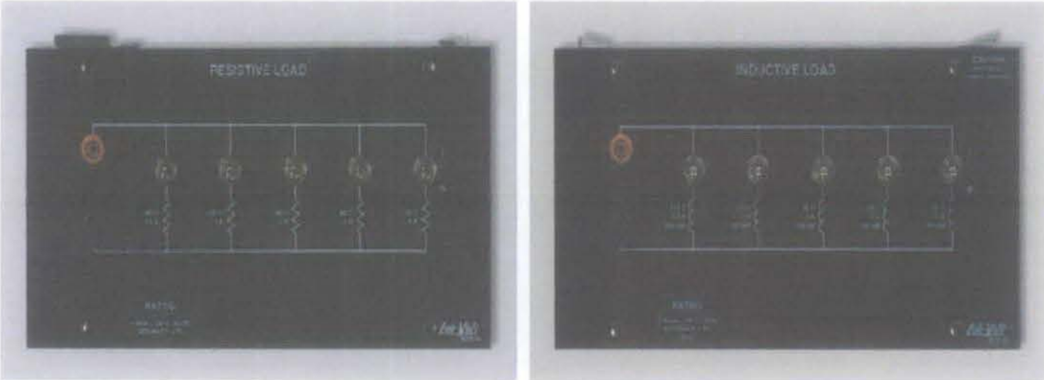


Figure 3.11: Lab Scaled Balanced Loads

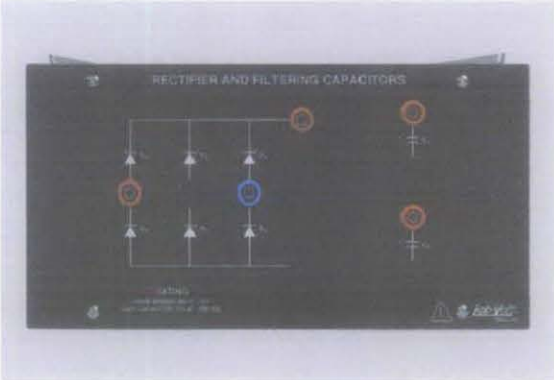


Figure 3.12: Lab Scaled Three Phase Full Bridge Rectifier

Figure 3.13: Field Rheostat

Figure 3.14: Power Supply

Figure 3.15: Connection Leads

The tool required for measuring the harmonics distortion is Fluke Three Phase Power Quality Analyzer. It is an ideal tool to conduct energy consumption studies and electrical load analysis, and to perform power quality logging and analysis. It is a complete three phase troubleshooting tool that measures virtually every power system parameter such as voltage, current, frequency, power, energy consumption, power factor, unbalance, harmonics and inter-harmonics. The Fluke Three Phase Power Quality Analyzer will be used together with the Flukeview software to transfer the data measured during the lab scaled experiment into a computer. The specifications of Fluke Three Phase Power Quality Analyzer were attached in Appendix B.

Figure 3.16: Fluke Three Phase Power Quality Analyzer

On the other hand, the main tool required for the modeling and simulation process is PSCAD software. PSCAD software is fast, accurate and easy-to-use power system simulation software for the design and verification of all types of power systems. PSCAD is most suitable for simulating time domain instantaneous responses, also known as electromagnetic transients or instantaneous solutions, in both electrical and control systems. The PSCAD graphical user interface greatly enhances the power and usability of the simulation environment. It allows the user to efficiently construct a circuit schematic, run a simulation, analyze the results, and manage the data in a completely integrated graphical environment. PSCAD provides intuitive and interactive control input, meters, and online plotting functions and graphs.

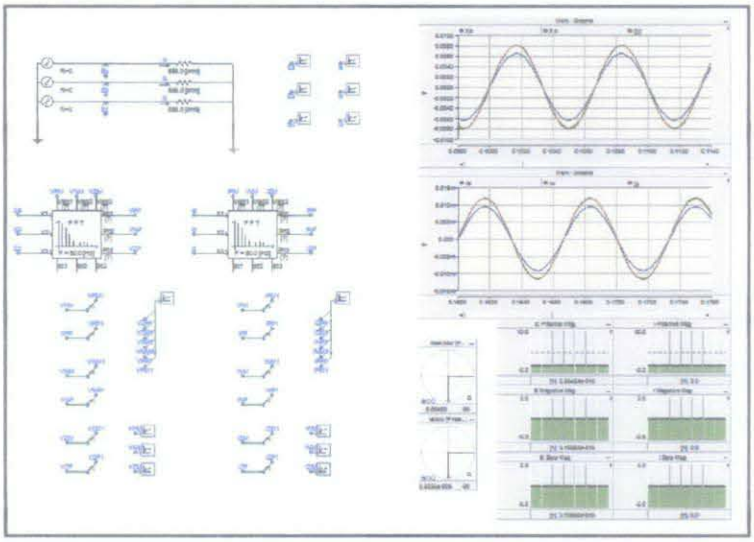


Figure 3.17: PSCAD Software

CHAPTER 4
RESULT AND DISCUSSION

4.1 Lab Experiment

In order to understand the characteristic of triplen harmonics current produced by synchronous generator when connected to non-linear load, results obtained from the lab experiments need to be compared. By comparing the synchronous generator without connected to non-linear load data with synchronous generator connected to the non-linear load data, we could actually see the effect of triplen harmonics current produced when both of them were connected together.

There are several results that need to be analyzed by comparing them with each other such as:

- Single Generator
  - Resistive load without full bridge rectifier and resistive load with full bridge rectifier
  - Inductive load without full bridge rectifier and inductive load with full bridge rectifier
  - Resistive and inductive load without full bridge rectifier and resistive and inductive load with full bridge rectifier

There are two types of voltages and currents that will be measured throughout the experiment, the fundamental and the triplen harmonics. Although the objective of this project is to study the propagation of triplen harmonics, the fundamental voltages and currents are measured in order to observe the difference gained from both studies. The difference between the fundamental and triplen harmonics in term of voltages and currents are shown through Appendix C to Appendix H respectively. The results and discussion on triplen harmonics voltages and currents produced will be further elaborated through Figure 4.1 to Figure 4.30.

4.1.1 Resistive Load without Full Bridge Rectifier and Resistive Load with Full Bridge Rectifier

- Resistive Load Without Full Bridge Rectifier

In single generator connected to resistive load without a full bridge rectifier experiment, the synchronous generator will be tested with five different values of resistive load which consist of 120 Ω, 160 Ω, 240 Ω, 320 Ω and 480 Ω. The voltages and currents of triplen harmonics will be measured at two different points, one will be at the generator and the other one will be at the load.

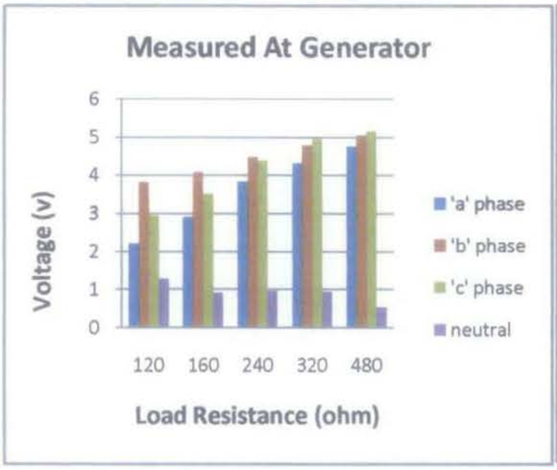


Figure 4.1: 3rd Harmonics Voltage Measured At Generator When Single Generator Connected To Various Resistive Loads without Rectifier

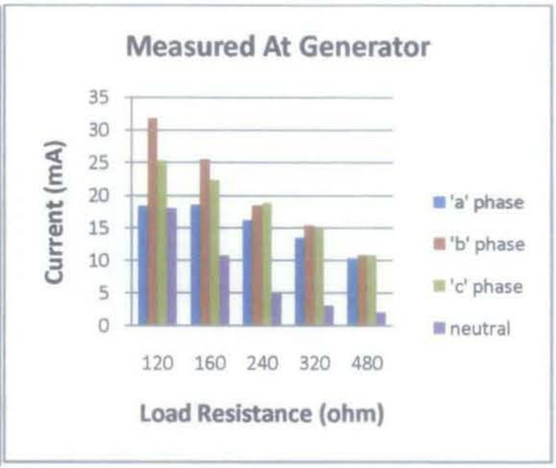
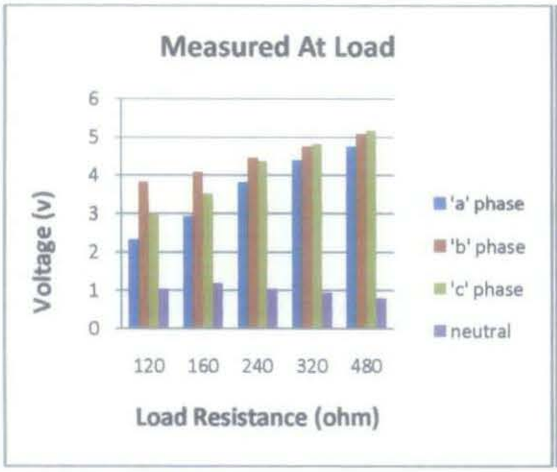


Figure 4.2: 3rd Harmonics Current Measured At Generator When Single Generator Connected To Various Resistive Loads without Rectifier



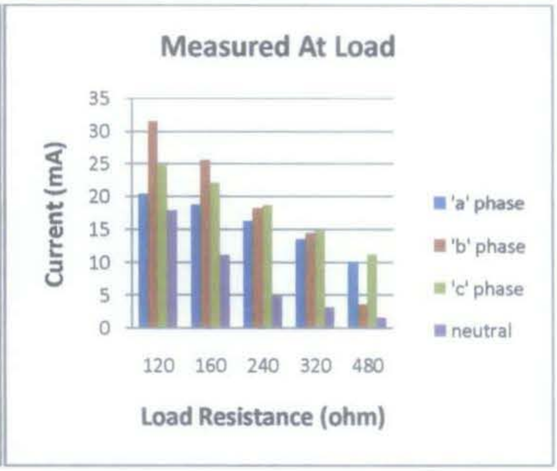
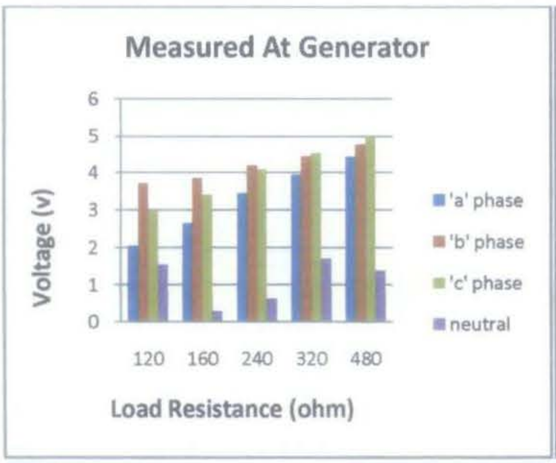


Figure 4.3: 3rd Harmonics Voltage Measured At Load When Single Generator Connected To Various Resistive Loads without Rectifier

Figure 4.4: 3rd Harmonics Current Measured At Load When Single Generator Connected To Various Resistive Loads without Rectifier

- Resistive Load With Full Bridge Rectifier

In single generator connected to resistive load with a full bridge rectifier experiment, the synchronous generator will also be tested with five different values of resistive load as mention in the previous experiment. Instead of having the generator connected directly to the load, the synchronous generator will also be connected to a rectifier. The voltages and currents of triplen harmonics will be measured at three different points, one will be at the generator, one will be at the load and one will be at the rectifier.



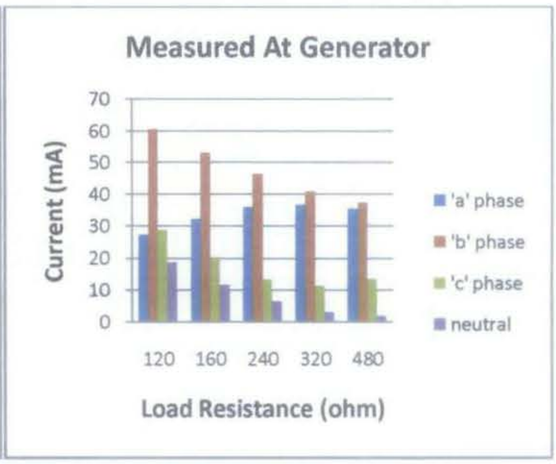


Figure 4.5: 3rd Harmonics Voltage Measured At Generator When Single Generator Connected To Various Resistive Loads with Rectifier

Figure 4.6: 3rd Harmonics Current Measured At Generator When Single Generator Connected To Various Resistive Loads with Rectifier

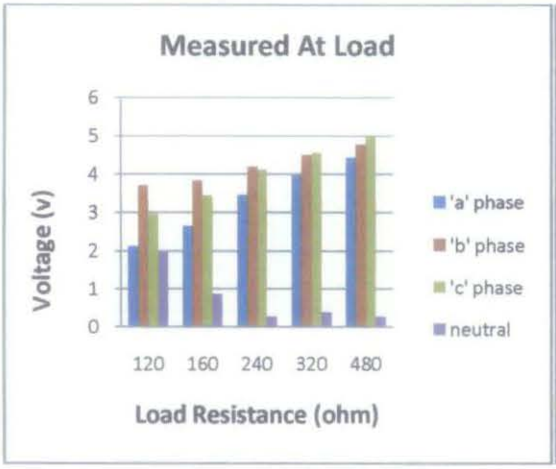


Figure 4.7: 3rd Harmonics Voltage Measured At Load When Single Generator Connected To Various Resistive Loads with Rectifier

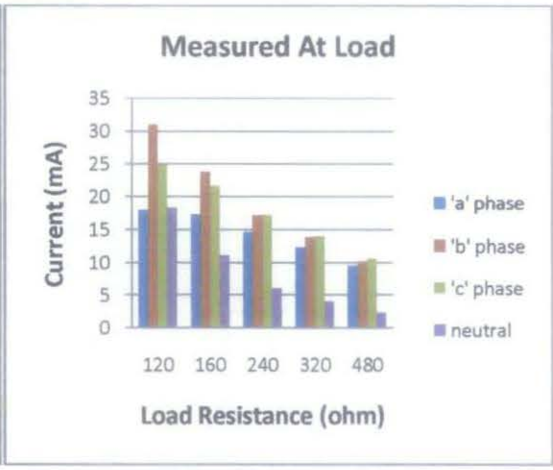


Figure 4.8: 3rd Harmonics Current Measured At Load When Single Generator Connected To Various Resistive Loads with Rectifier

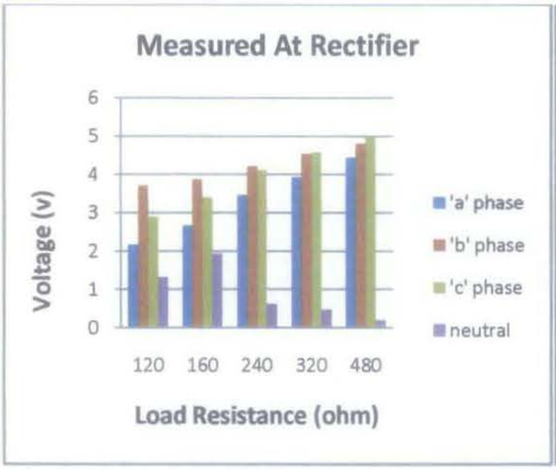


Figure 4.9: 3rd Harmonics Voltage Measured At Rectifier When Single Generator Connected To Various Resistive Loads with Rectifier

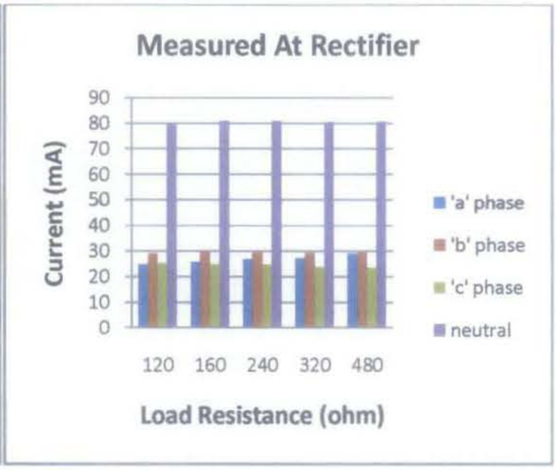


Figure 4.10: 3rd Harmonics Current Measured At Rectifier When Single Generator Connected To Various Resistive Loads with Rectifier

By comparing the graph representation of triplen harmonics voltage of resistive load without connected to the rectifier with resistive load connected to the rectifier, we can observe that there is no significance difference on the magnitude of the triplen harmonics voltage either at generator side, at load side or at rectifier side. As the value of load resistance increase, the magnitude of the triplen harmonics voltage also increases.

On the other hand, by comparing the graph of triplen harmonics current of resistive load without connected to the rectifier with resistive load connected to the rectifier, we can observe at the generator side and at the load side, the magnitude of the triplen harmonics current decreases as the value of load resistance increases. The magnitude of triplen harmonics current measured at rectifier show no change in term of magnitude as the load resistance value increases.

Despite having the same trend, we can see that at the generator side, the magnitude of triplen harmonics current of resistive load connected to the rectifier are slightly higher at red, blue and yellow phases compare to the magnitude of triplen harmonics current of resistive load without connected to the rectifier.

Since the phase angle measured at the generator side and at the load side are in positive sequence, the triplen harmonics current will not be additive in neutral. In contrast, the phase angle measured at the rectifier side is in zero sequence, thus, justify the high neutral current since the triplen harmonics current is additive in neutral.

The difference in triplen harmonics current magnitude measured at the generator side between the resistive loads without connected to the rectifier with resistive load connected to the rectifier was caused by the neutral current produced in the rectifier that flows through the neutral line. Since the rectifier neutral line is connected to the generator, the neutral current flows into the generator and affects the generator current magnitude.

4.1.2 Inductive Load without Full Bridge Rectifier and Inductive Load with Full Bridge Rectifier

- Inductive Load Without Full Bridge Rectifier

In single generator connected to inductive load without a full bridge rectifier experiment, the synchronous generator will be tested with five different values of inductive load which consist of 0.38 H, 0.51 H, 0.76 H, 1.02 H and 1.53 H. The voltages and currents of triplen harmonics will be measured at two different points, one will be at the generator and the other one will be at the load.

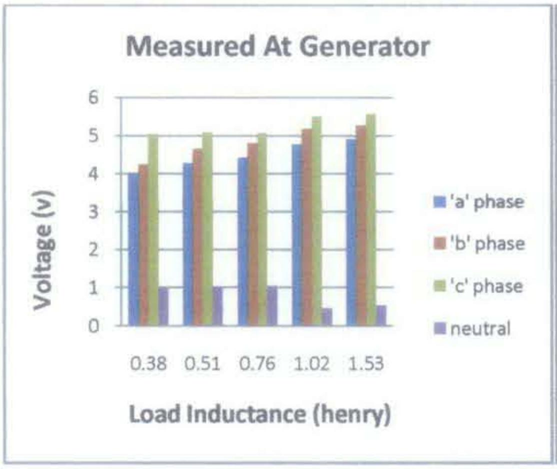


Figure 4.11: 3rd Harmonics Voltage Measured At Generator When Single Generator Connected To Various Inductive Loads without Rectifier

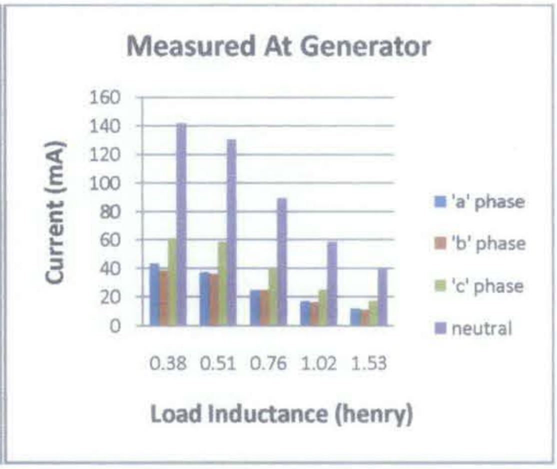


Figure 4.12: 3rd Harmonics Current Measured At Generator When Single Generator Connected To Various Inductive Loads without Rectifier

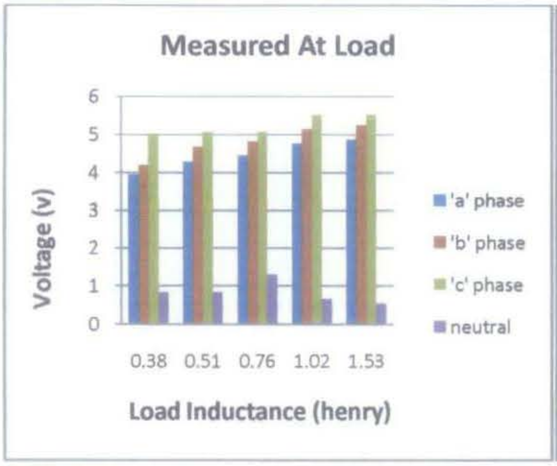


Figure 4.13: 3rd Harmonics Voltage Measured At Load When Single Generator Connected To Various Inductive Loads without Rectifier

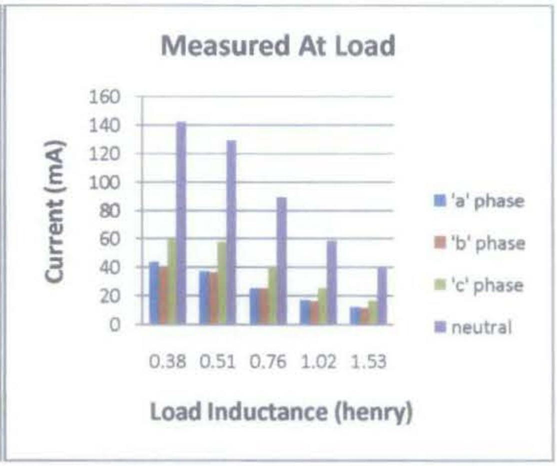


Figure 4.14: 3rd Harmonics Current Measured At Load When Single Generator Connected To Various Inductive Loads without Rectifier

- Inductive Load With Full Bridge Rectifier

In single generator connected to inductive load with a full bridge rectifier experiment, the synchronous generator will also be tested with five different values of inductive load as mention in the previous experiment. Instead of having the generator connected directly to the load, the synchronous generator will also be connected to a rectifier. The voltages and currents of triplen harmonics will be measured at three different points, one will be at the generator, one will be at the load and one will be at the rectifier.

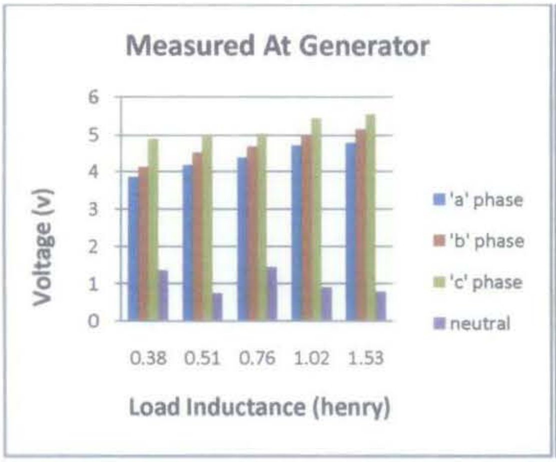


Figure 4.15: 3rd Harmonics Voltage Measured At Generator When Single Generator Connected To Various Inductive Loads with Rectifier

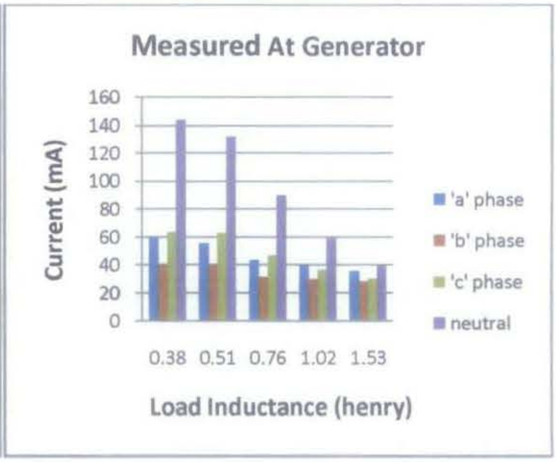


Figure 4.16: 3rd Harmonics Current Measured At Generator When Single Generator Connected To Various Inductive Loads with Rectifier

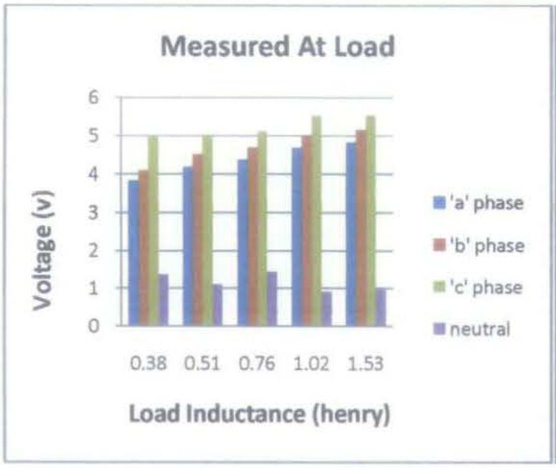


Figure 4.17: 3rd Harmonics Voltage Measured At Load When Single Generator Connected To Various Inductive Loads with Rectifier

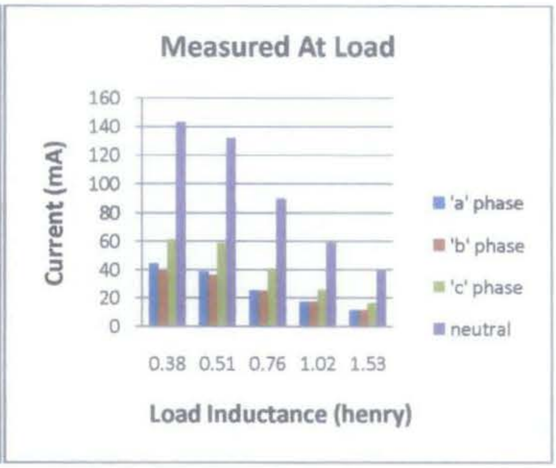


Figure 4.18: 3rd Harmonics Current Measured At Load When Single Generator Connected To Various Inductive Loads with Rectifier

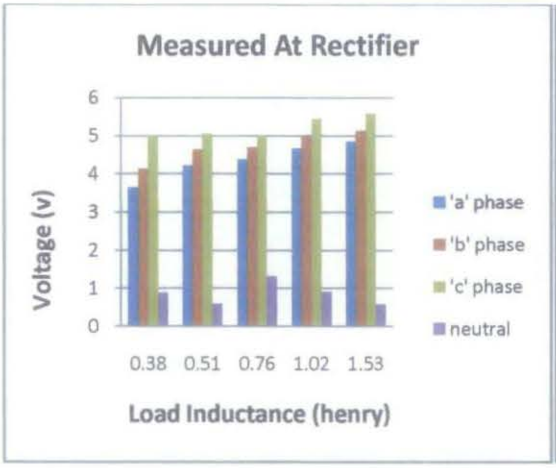


Figure 4.19: 3rd Harmonics Voltage Measured At Rectifier When Single Generator Connected To Various Inductive Loads with Rectifier

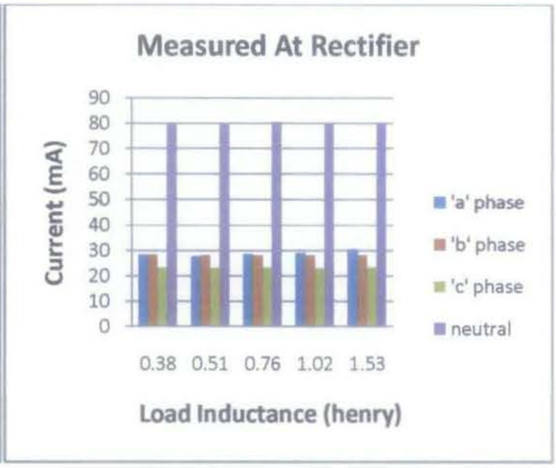


Figure 4.20: 3rd Harmonics Current Measured At Rectifier When Single Generator Connected To Various Inductive Loads with Rectifier

By comparing the graph representation of triplen harmonics voltage of inductive load without connected to the rectifier with inductive load connected to the rectifier, we can observe that there is no significance difference on the magnitude of the triplen harmonics voltage either at generator side, at load side or at rectifier side. As the value of load inductance increase, the magnitude of the triplen harmonics voltage also increases.

On the other hand, by comparing the graph of triplen harmonics current of inductive load without connected to the rectifier with inductive load connected to the rectifier, we can observe at the generator side and at the load side, the magnitude of the triplen harmonics current decreases as the value of load inductance increases. The magnitude of triplen harmonics current measured at rectifier show no change in term of magnitude as the load inductance value increases.

Despite having the same trend, we can see that at the generator side, the magnitude of triplen harmonics current of inductive load connected to the rectifier are slightly higher at red, yellow and blue phases compared to the magnitude of triplen harmonics current of inductive load without connected to the rectifier.

Since the phase angle measured at the generator side, at the load side and at the rectifier side are in zero sequence, the triplen harmonics current is additive in neutral. Thus, justify the high neutral current. We can conclude here that when generator is connected to balanced inductive load, the third harmonic generated is higher.

The difference in triplen harmonics current magnitude measured at the generator side between the inductive loads without connected to the rectifier with inductive load connected to the rectifier was caused by the neutral current produced in the rectifier that flows through the neutral line. Since the rectifier neutral line is connected to the generator, the neutral current flows into the generator and affects the generator current magnitude.

4.1.3 Resistive and Inductive Load without Full Bridge Rectifier and Resistive and Inductive Load with Full Bridge Rectifier

- Resistive And Inductive Load Without Full Bridge Rectifier

In single generator connected to resistive and inductive load without a full bridge rectifier experiment, the synchronous generator will be tested with five different values of resistive and inductive load which consist of Case 1 = 120 Ω + 0.38 H, Case 2 = 160 Ω + 0.51 H, Case 3 = 240 Ω + 0.76 H, Case 4 = 320 Ω + 1.02 H and Case 5 = 480 Ω + 1.53 H. The voltages and currents of triplen harmonics will be measured at two different points, one will be at the generator and the other one will be at the load.

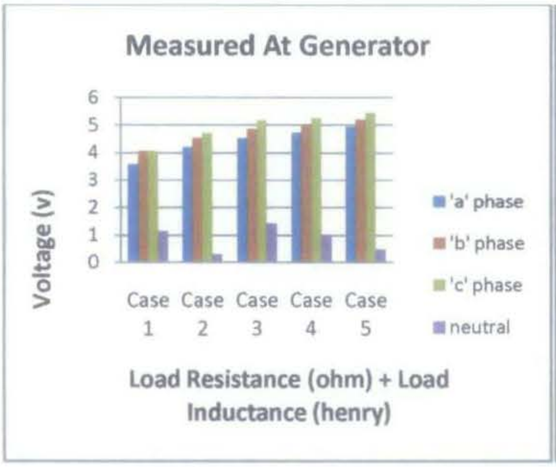


Figure 4.21: 3rd Harmonics Voltage Measured At Generator When Single Generator Connected To Various Resistive & Inductive Loads without Rectifier

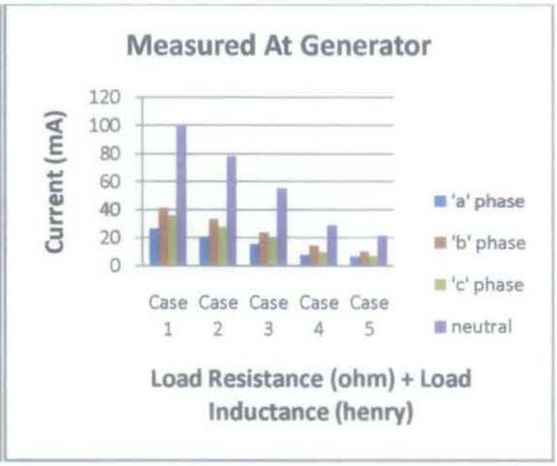


Figure 4.22: 3rd Harmonics Current Measured At Generator When Single Generator Connected To Various Resistive & Inductive Loads without Rectifier

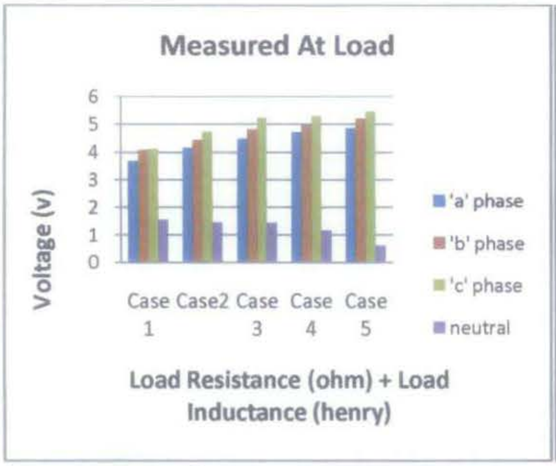


Figure 4.23: 3rd Harmonics Voltage Measured At Load When Single Generator Connected To Various Resistive & Inductive Loads without Rectifier

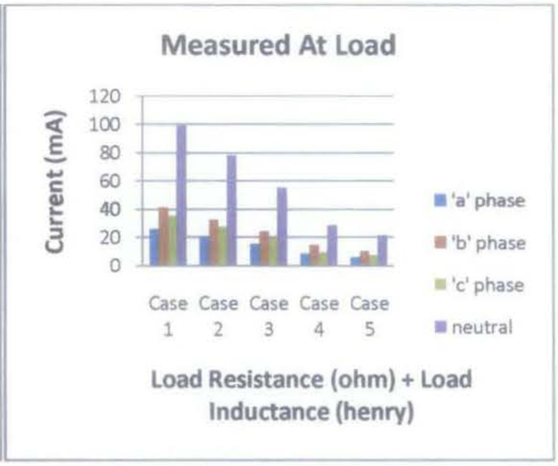


Figure 4.24: 3rd Harmonics Current Measured At Load When Single Generator Connected To Various Resistive & Inductive Loads without Rectifier

- Resistive And Inductive Load With Full Bridge Rectifier

In single generator connected to resistive and inductive load with a full bridge rectifier experiment, the synchronous generator will also be tested with five different values of load as mention in the previous experiment. Instead of having the generator connected directly to the load, the synchronous generator will also be connected to a rectifier. The voltages and currents of triplen harmonics will be measured at three different points, one will be at the generator, one will be at the load and one will be at the rectifier.

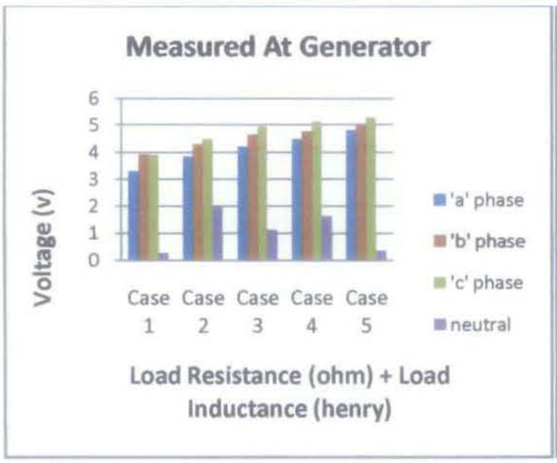


Figure 4.25: 3rd Harmonics Voltage Measured At Generator When Single Generator Connected To Various Resistive & Inductive Loads with Rectifier

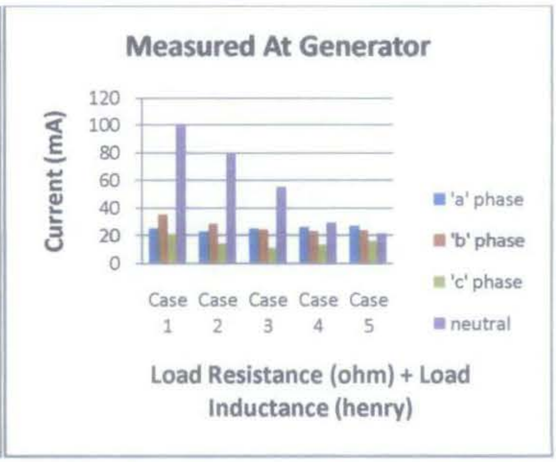


Figure 4.26: 3rd Harmonics Current Measured At Generator When Single Generator Connected To Various Resistive & Inductive Loads with Rectifier

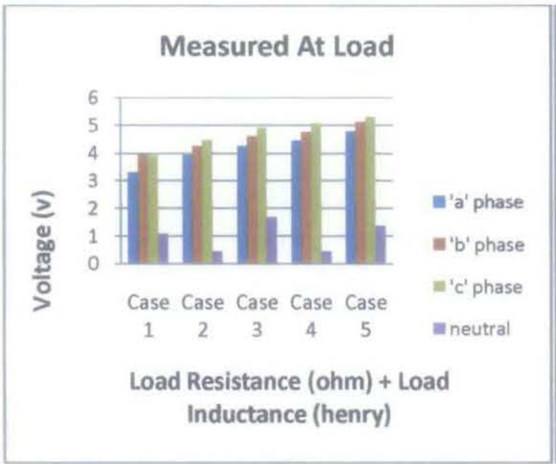


Figure 4.27: 3rd Harmonics Voltage Measured At Load When Single Generator Connected To Various Resistive & Inductive Loads with Rectifier

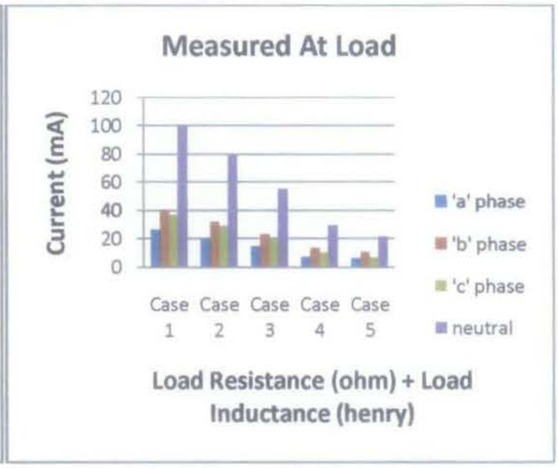


Figure 4.28: 3rd Harmonics Current Measured At Load When Single Generator Connected To Various Resistive & Inductive Loads with Rectifier

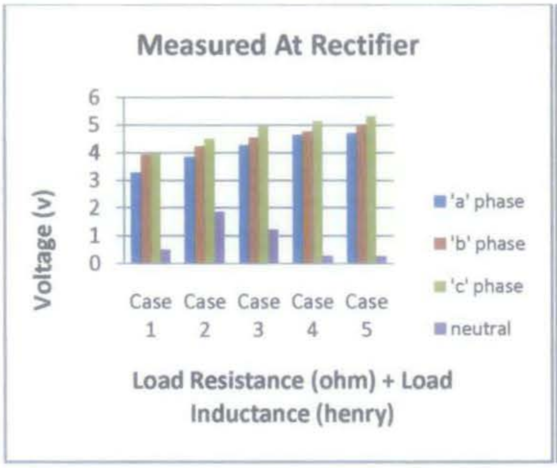


Figure 4.29: 3rd Harmonics Voltage Measured At Rectifier When Single Generator Connected To Various Resistive & Inductive Loads with Rectifier

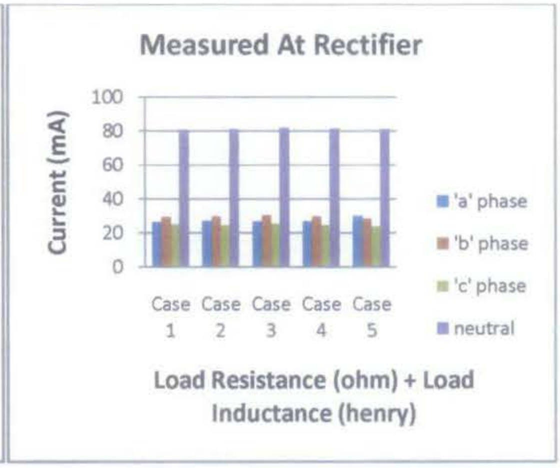


Figure 4.30: 3rd Harmonics Current Measured At Rectifier When Single Generator Connected To Various Resistive & Inductive Loads with Rectifier

By comparing the graph representation of triplen harmonics voltage of resistive and inductive load without connected to the rectifier with resistive and inductive load connected to the rectifier, we can observe that there is no significance difference on the magnitude of the triplen harmonics voltage either at generator side, at load side or at rectifier side. As the value of resistance and inductance increase, the magnitude of the triplen harmonics voltage also increases.

On the other hand, by comparing the graph of triplen harmonics current of resistive and inductive load without connected to the rectifier with resistive and inductive load connected to the rectifier, we can observe at the generator side and at the load side, the magnitude of the triplen harmonics current decreases as the value of resistance and inductance increases. The magnitude of triplen harmonics current measured at rectifier show no change in term of magnitude as the resistance and inductance value increases.

Despite having the same trend, we can see that at the generator side, the magnitude of triplen harmonics current of resistive and inductive load connected to the rectifier is slightly higher at red, yellow and blue phases compared to the magnitude of triplen harmonics current of resistive and inductive load without connected to the rectifier.

Since the phase angle measured at generator side, at load side and at rectifier side are in zero sequence, the triplen harmonics current is additive in neutral. Thus, justify the high neutral current.

The difference in triplen harmonics current magnitude measured at the generator side between the resistive and inductive load without connected to the rectifier with resistive and inductive load connected to the rectifier was caused by the neutral current produced in the rectifier that flows through the neutral line. Since the rectifier neutral line is connected to the generator, the neutral current flows into the generator and affects the generator current magnitude.

4.2 PSCAD Simulation Modeling

In order to model the lab scaled experiment results, it is necessary to run simulation modeling on triplen harmonics current produced by synchronous generator when connected to non-linear load by using PSCAD software. Results obtained from the PSCAD simulation modeling will be compared with the results obtained from the lab scaled experiment in order to obtain the best and accurate results.

To ensure that the PSCAD simulation modeling result can be compared directly with the lab scaled experiment results, it is crucial for the model development be held according to the same setup based on the operating parameters used in the lab scaled experiment.

There are several simulations modeling that have been conducted such as:

- Single Generator
  - Connected to resistive load
  - Connected to inductive load
  - Connected to resistive and inductive load

4.2.1 Single Generator Connected To Resistive Load

In single generator connected to resistive load simulation modeling, the setup and parameter used in PSCAD software will be the same as the one used in the lab scaled experiment with five different values of resistive load which consist of 120 Ω, 160 Ω, 240 Ω, 320 Ω and 480 Ω. The triplen harmonics voltage and current will only be measured at the load side. In this simulation, the voltage source is modeled using third harmonics voltage sources. The magnitude of harmonics voltages, phase angle and frequency is used as voltage sources.

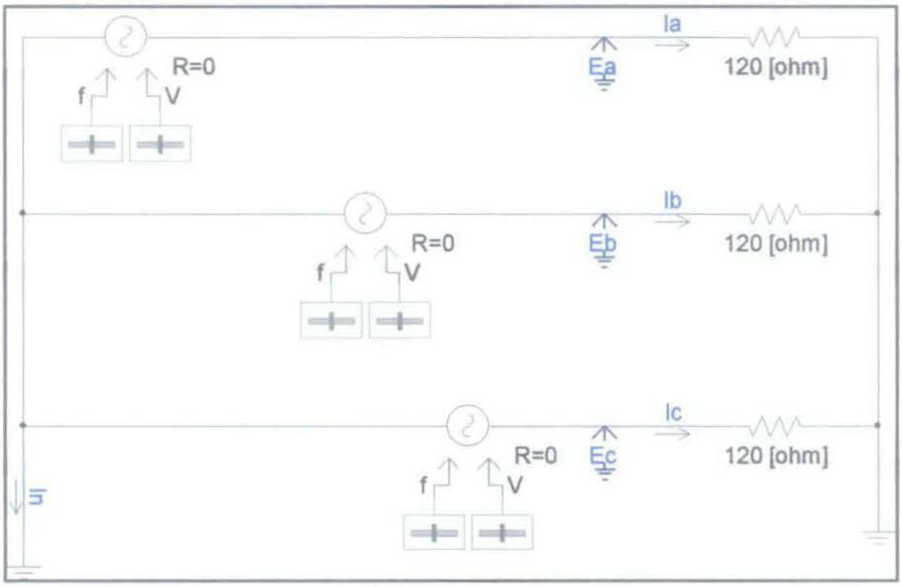


Figure 4.31: Simulation Modeling Of Single Generator Connected To Resistive Load

Table 4.1: Triplen Harmonics Voltage and Current When Single Generator Connected To Various Resistive Loads

R (Ohm)	Va V	Vb V	Vc V	Ia mA	Ib mA	Ic mA	In mA
120	0.010610	0.011370	0.031360	0.08849	0.094780	0.261300	0.26440
160	0.001521	0.001579	0.001142	0.009507	0.009867	0.007137	0.02595
240	0.011670	0.012250	0.015970	0.048640	0.051030	0.066530	0.16610
320	0.059200	0.064460	0.063340	0.185000	0.201400	0.197900	0.58430
480	0.003715	0.005060	0.008986	0.007741	0.010540	0.018720	0.03697

Based on Table 4.1, the triplen harmonics voltage and current value obtained from the simulation were plotted into graph as shown in Figure 4.32 and Figure 4.33.

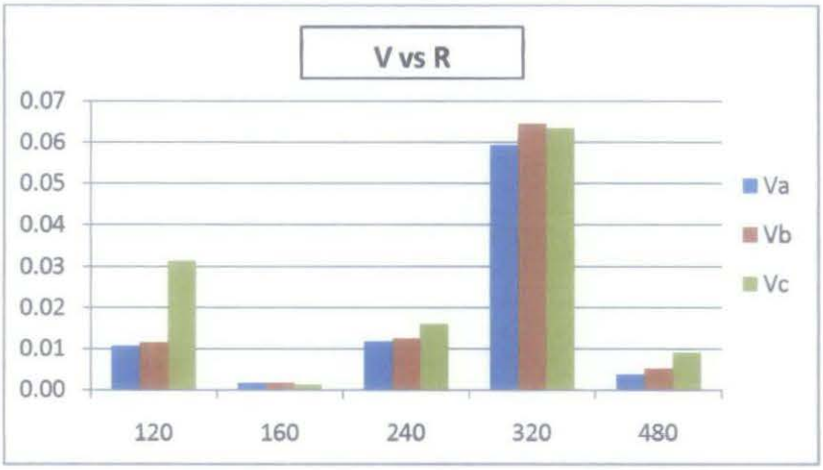


Figure 4.32: Graph of Triplen Harmonics Voltage Vs Resistance When Single Generator Connected To Various Resistive Loads

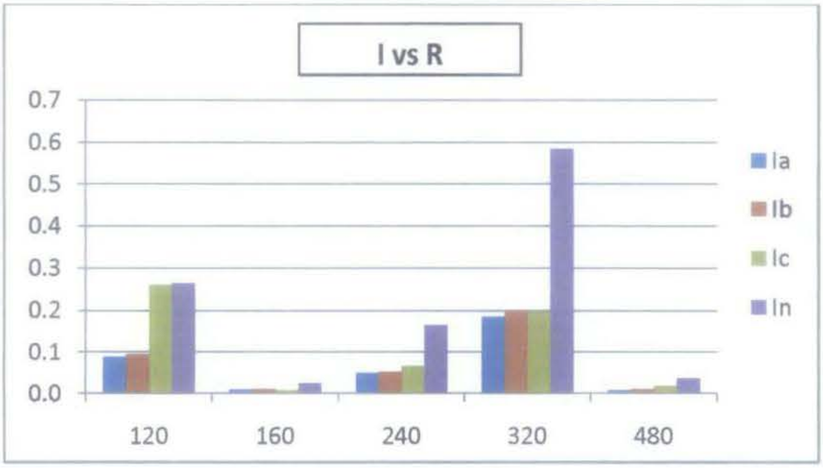


Figure 4.33: Graph of Triplen Harmonics Current Vs Resistance When Single Generator Connected To Various Resistive Loads

As we can see, the simulation results are a slight different than the experiment data. The voltage and current for 160 Ω and 480 Ω were too low to compare with the experiment result. This model is still in trial and error process because the correct source used in the experiment could never be identified by the software in order to give the desired outputs. This model still needs improvement and hopefully it will be done in the future.

4.2.2 Single Generator Connected To Inductive Load

In single generator connected to inductive load simulation modeling, the setup and parameter used in PSCAD software will be the same as the one used in the lab scaled experiment with five different values of inductive load which consist of 0.38 H, 0.51 H, 0.76 H, 1.02 H and 1.53 H. The triplen harmonics voltage and current will only be measured at the load side. Same as the single generator connected to resistive load condition, the voltage source is modeled using third harmonics voltage sources. The voltage source is used with third harmonics voltage magnitude, phase angle and frequency.

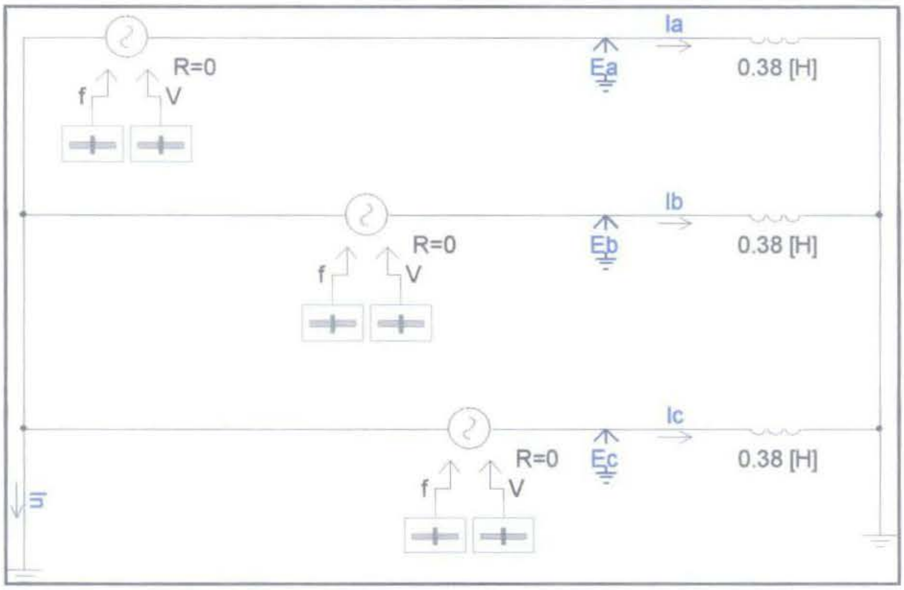


Figure 4.34: Simulation Modeling Of Single Generator Connected To Inductive Load

Table 4.2: Triplen Harmonics Voltage and Current When Single Generator Connected To Various Inductive Loads

L (H)	Va V	Vb V	Vc V	Ia mA	Ib mA	Ic mA	In mA
0.38	0.01607	0.01755	0.02152	0.015070	0.017240	0.022230	0.05440
0.51	0.01664	0.01800	0.02341	0.010780	0.011660	0.025130	0.04510
0.76	0.02136	0.02291	0.02402	0.023730	0.029750	0.032840	0.08629
1.02	0.02242	0.02366	0.02560	0.014210	0.012000	0.013740	0.03987
1.53	0.01329	0.01554	0.02053	0.003362	0.003578	0.004246	0.01059

Based on Table 4.2, the triplen harmonics voltage and current value obtained from the simulation were plotted into graph as shown in Figure 4.35 and Figure 4.36.

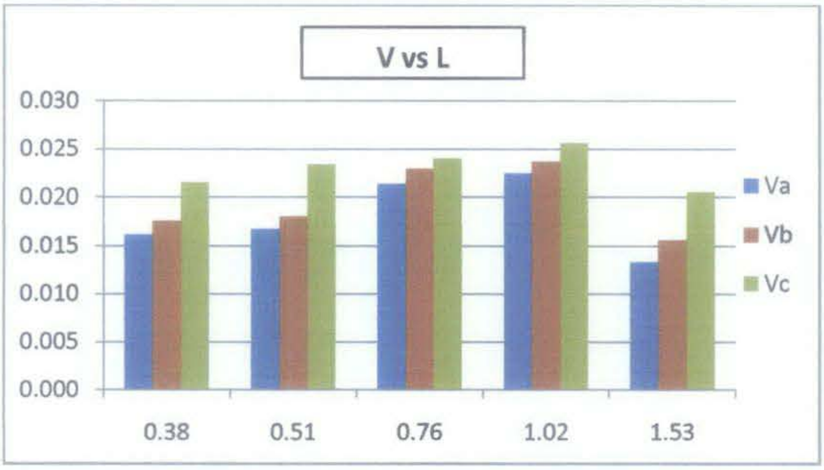


Figure 4.35: Graph of Triplen Harmonics Voltage Vs Inductance When Single Generator Connected To Various Inductive Loads

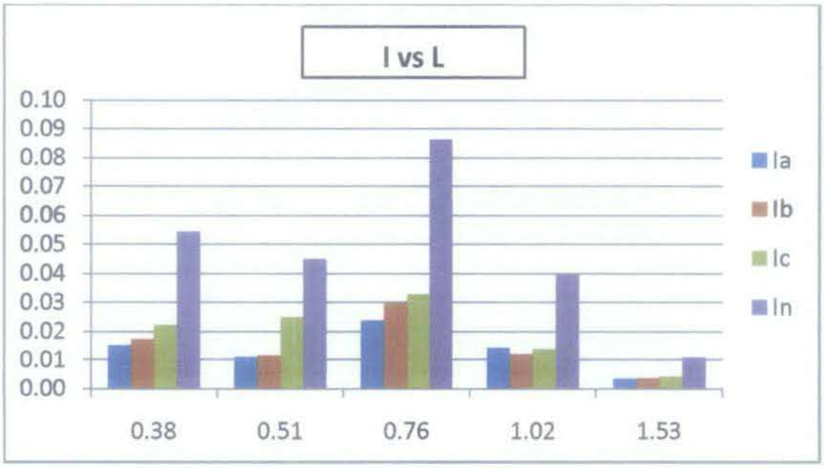


Figure 4.36: Graph of Triplen Harmonics Current Vs Inductance When Single Generator Connected To Various Inductive Loads

As we can see, the outputs from the simulation are slightly different from the actual data gained during experiment. This model is still in trial and error process because the correct source used in the experiment could never be identified by the software in order to give the desired outputs. This model still needs improvement and hopefully it will be done in the future.

4.2.3 Single Generator Connected To Resistive and Inductive Load

In single generator connected to resistive and inductive load simulation modeling, the setup and parameter used in PSCAD software will be the same as the one used in the lab scaled experiment with five different values of resistive and inductive load which consist of Case 1 = 120 Ω + 0.38 H, Case 2 = 160 Ω + 0.51 H, Case 3 = 240 Ω + 0.76 H, Case 4 = 320 Ω + 1.02 H and Case 5 = 480 Ω + 1.53 H. The triplen harmonics voltage and current will only be measured at the load side. For this simulation, the voltage source is also modeled using third harmonics voltage sources. The magnitude of harmonics voltages, phase angle and frequency is used as voltage sources.

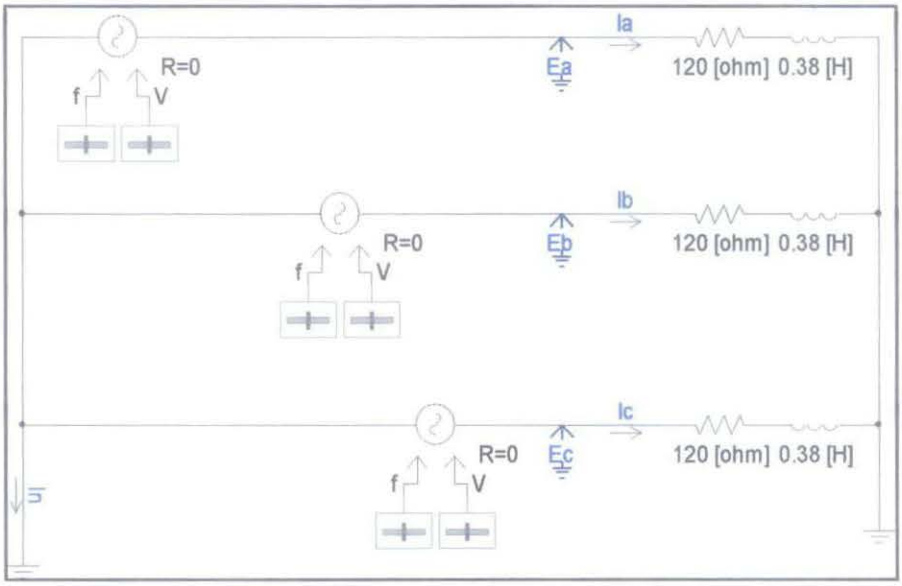


Figure 4.37: Simulation Modeling Of Single Generator Connected To Resistive and Inductive Load

Table 4.3: Triplen Harmonics Voltage and Current When Single Generator Connected To Various Resistive & Inductive Loads

R+L (ohm)+(H)	R+L	Va V	Vb V	Vc V	Ia mA	Ib mA	Ic mA	In mA
Case 1	120 + 0.38	0.016700	0.019580	0.018020	0.034720	0.062540	0.073480	0.170200
Case 2	160 + 0.51	0.011250	0.019530	0.030210	0.071210	0.075670	0.072920	0.218700
Case 3	240 + 0.76	0.017470	0.019870	0.017220	0.044400	0.046130	0.055290	0.145800
Case 4	320 + 1.02	0.000325	0.002431	0.004127	0.000325	0.001735	0.002406	0.004453
Case 5	480 + 1.53	0.003819	0.007658	0.010040	0.001484	0.002011	0.002256	0.005596

Based on Table 4.3, the triplen harmonics voltage and current value obtained from the simulation were plotted into graph as shown in Figure 4.38 and Figure 4.39.

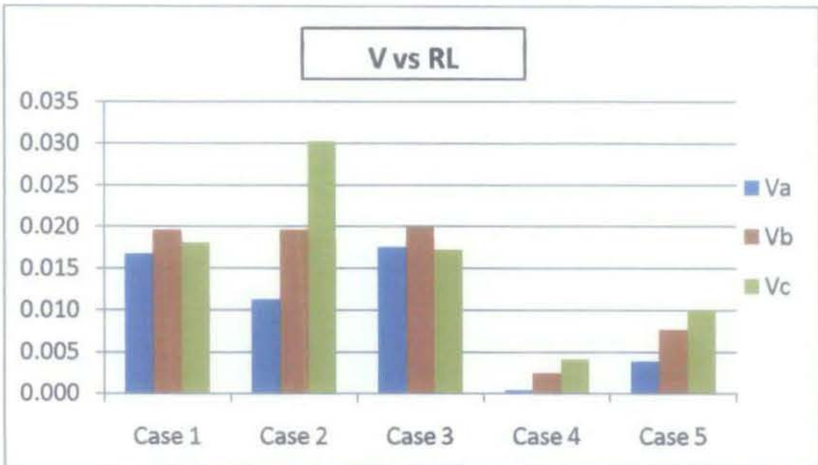


Figure 4.38: Graph of Triplen Harmonics Voltage Vs Resistance & Inductance When Single Generator Connected To Various Resistive and Inductive Loads

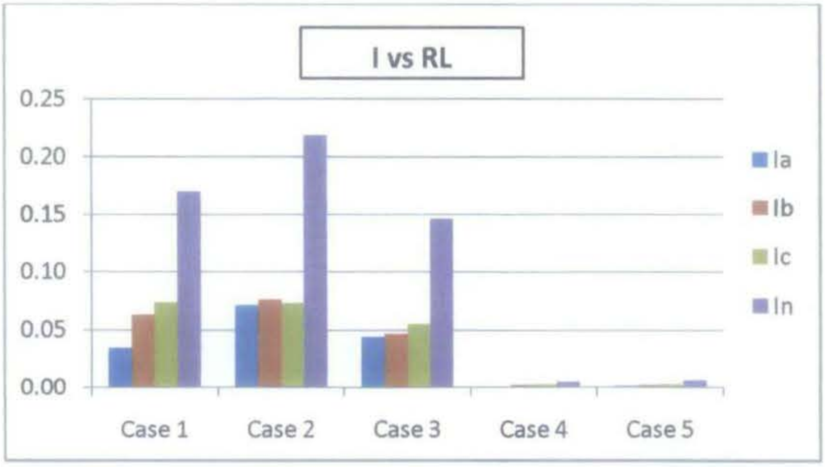


Figure 4.39: Graph of Triplen Harmonics Current Vs Resistance & Inductance When Single Generator Connected To Various Resistive and Inductive Loads

As we can see, the simulation results are a slight different than the experiment data. The voltage and current for Case 4 and Case 5 were too low for comparison with the result obtained during the experiment. This model is still in trial and error process because the correct source used in the experiment could never be identified by the software in order to give the desired outputs. This model still needs improvement and hopefully it will be done in the future.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Based on all the outcomes obtained, we can conclude that when the synchronous generator is connected to balanced resistive load, the triplen harmonics current produced are in positive sequence. The triplen harmonics current produced when synchronous generator is connected to balanced inductive load is the highest compared to synchronous generator when connected to any other balanced load. We can also conclude that the triplen harmonics current produced by the rectifier will add up in the neutral line which flows toward the generator and affect the current magnitude of the generator. It is proved that the development of a triplen harmonics current produced when synchronous generator is connected to non-liner load is a good project as it could help to improve the system in the networks. There is a possibility that it can be applied to plants as it has the potential of saving huge amount of maintenance cost to the power generating companies.

5.2 Recommendation

For further thorough analysis regarding triplen harmonics current produced by synchronous generator when connected to non-linear load, it is recommended to do researches that include more than one type of non-linear load. This is to ensure that the results obtained are more accurate to describe the effect of triplen harmonics current produced when both of them were connected together. Besides, a long period of studies need to be considered which will include another part in the experiment which consist of single generator connected parallel to the grid and two generator connected in parallel so that a proper standards can be performed and implied in the industrial sector. This can provide us more understanding on the effect of triple harmonics current produced by synchronous generator when connected to non-linear load and give is the opportunity for any improvement in the future.

REFERENCES

[1] Roger C. Dugan, Mark F. McGranaghan, Surya Santoso, H. Wayne Beaty, "Electrical Power Systems Quality", McGraw-Hill, 2003

[2] Gregory W. Massey, "Power distribution system design for operation under non-sinusoidal load conditions," IEEE Transactions on Industry Applications, Vol. 31, pp. 513-519, No. 3, May/June 1995

[3] Selkirk D., Savostianik M., Crawford K., "Why neutral-grounding resistors need continuous monitoring," Petroleum and Chemical Industry Technical Conference, 2008

[4] Paul G. Cardinal, "Generator pitch and associated concerns when paralleling generators," Industry Applications Society Annual Meeting, 2009.

[5] M. F. Abdullah, N. H. Hamid, Z. Baharudin, M. F. I. Khamis, N. S. R. Hashim, S. Yusof, "Investigation On High Neutral Earthing Resistor Temperature When Islanded Generator Connected To Utility Grid," The 9th International Power and Energy Conference, Oct. 2010

[6] Louie J. Powell, Jr., "Influence of third harmonic circulating currents in selecting neutral grounding devices," IEEE Transactions on Industry Applications, Vol. 1A-9, pp. 672-679, No. 6, November/December 1973

APPENDICES

Appendix A: Lab – Volt 2 kW Electromechanical Training System Specifications

Model 8013 – 2-kW Electromechanical Training System				
Power Requirement		Refer to the specifications of the Power Supply, Model 8525		
Physical Characteristics	Dimensions (H x W x D)	855 x 440 x 775 mm (33.7 x 17.3 x 30.5 in)		
	Net Weight: System 8013-1	963 kg (2119 lb)		
	System 8013-2	351 kg (772 lb)		
	System 8013-3	532 kg (1070 lb)		
	System 8013-4	948 kg (2086 lb)		
Model 8501 – DC Motor/Generator		**120/208 V – 60 Hz**	**220/380 V – 50 Hz**	**240/415 V – 50 Hz**
Motor (Full Load / Shunt)	Power	2 kW		
	Armature Voltage	120 V – DC	220 V – DC	240 V – DC
	Shunt-Field Voltage	120 V – DC	220 V – DC	240 V – DC
	Speed	1800 r/min	1500 r/min	
	Current	23 A	12.1 A	11.4 A
	Torque	10.6 N·m (93.8 lbf·in)	12.7 N·m (112.4 lbf·in)	
	Efficiency	70%	73%	70%
	Nominal Shunt-Field Current	0.81 A	0.44 A	0.43 A
	Friction and Windage Losses	130 W	110 W	
	Iron Losses	55 W	40 W	
Generator (Full Load / Shunt)	Power	1.5 kW		
	Speed	1800 r/min	1500 r/min	
	Current	12.5 A	6.8 A	6.2 A
	Efficiency	83%	85%	81%
	Nominal Shunt-Field Current	1.12 A	0.60 A	0.56 A
	Friction and Windage Losses	130 W	110 W	
	Iron Losses	90 W	70 W	
Resistances at 25° C	Shunt (1-2)	69 Ω	255 Ω	278 Ω
	Short-Series (3-4)	0.14 Ω	0.33 Ω	0.36 Ω
	Long-Series (5-6)	0.24 Ω	0.70 Ω	0.77 Ω
	Interpoles (7-8)	0.32 Ω	1.23 Ω	
	Armature and Brushes (8-9)	0.35 Ω	1.15 Ω	
Inductances	Shunt Field (1-2)	4.4 H	12.4 H	14.8 H
	Armature (8-9)	8.7 mH	45.6 mH	
Search Coils	Stator - One Pole	10 turns		
	Armature - Full Pitch	5 turns		
	Armature One - Tooth	5 turns		
Torque Indicator		0 to 30 N·m (0 to 266 lbf·in)		
Physical Characteristics	Moment of Inertia	0.14 kg·m² (478 lb·in²)		
	Dimensions (H x W x D)	855 x 440 x 775 mm (33.7 x 17.3 x 30.5 in)		
	Net Weight	129 kg (283.8 lb)		
Model 8502 – Wiring Module for DC Motor/Generator				
Physical Characteristics	Dimensions (H x W x D)	212 x 287 x 496 mm (8.3 x 11.3 x 19.5 in)		
	Net Weight	4.1 kg (9.0 lb)		

Model 8507 – Three-Phase Synchronous Motor/Generator		**120/208 V – 60 Hz**	**220/380 V – 50 Hz**	**240/415 V – 50 Hz**
Motor (Full Load)	Connection	3 ~, wye connected		
	Line Voltage	120/208 V – 60 Hz	220/380 V – 50 Hz	240/415 V – 50 Hz
	Power	2 kW		
	Speed	1800 r/min	1500 r/min	
	Current	6.8 A	3.6 A	3.3 A
	Exciter Current	1 A – DC	0.55 A – DC	
	Torque	10.6 N·m (93.8 lbf·in)	12.7 N·m (112.4 lbf·in)	
	Efficiency	80%	80%	83%
	Friction and Windage Losses	150 W	110 W	
	Iron Losses	125 W	80 W	
Motor (Starting)	Current	34 A	18 A	16.5 A
	Torque	24.0 N·m (212.4 lbf·in)	30.0 N·m (265.5 lbf·in)	
Generator	Connection	3 ~, wye connected		
	Power	1.5 kVA		
	Current	4.2 A – AC	2.3 A – AC	2.1 A – AC
	Exciter Current	0.9 A – DC	0.53 A – DC	0.5 A – DC
	Efficiency	79%	81%	
Resistance (per phase at 25° C)	Stator	0.6 Ω	2.2 Ω	2.3 Ω
	Rotor	81 Ω	236 Ω	246 Ω
Synchronous Reactance		18.5 Ω	77 Ω	96 Ω
Exciter Inductance		6 H	21.9 H	26 H
Search Coils	Stator - One Pole - Full Pitch	5 turns		
	Rotor - One Pole	5 turns		
Physical Characteristics	Moment of Inertia	0.097 kg·m² (331.5 lb·in²)		
	Dimensions (H x W x D)	830 x 400 x 605 mm (32.7 x 15.7 x 23.8 in)		
	Net Weight	89 kg (195.8 lb)		
Model 8508 – Wiring Module for Synchronous Motor/Generator				
Physical Characteristics	Dimensions (H x W x D)	212 x 287 x 496 mm (8.3 x 11.3 x 19.5 in)		
	Net Weight	4.1 kg (9.0 lb)		
Model 8509 – Resistive Load		**120/208 V – 60 Hz**	**220/380 V – 50 Hz**	**240/415 V – 50 Hz**
Resistors	Number	5		
	Resistance	240/120/60/60/30 Ω	880/440/220/220/110 Ω	960/480/240/240/120 Ω
	Nominal Voltage	120 V – AC/DC	220 V – AC/DC	240 V – AC/DC
	Accuracy	5%		
Toggle Switch	Number	5 - connected in series with each resistor		
Load at Nominal Voltage	Power	60 to 1170 W	55 to 1045 W	60 to 1040 W
	Current	0.5 to 9.5 A	0.25 to 4.75 A	
	Number of Steps	19 of equal increment		
	Current Increment	0.5 A	0.25 A	
Physical Characteristics	Dimensions (H x W x D)	154 x 287 x 440 mm (6.1 x 11.3 x 17.3 in)		
	Net Weight	6.3 kg (13.9 lb)		

Model 8510 – Inductive Load		120/208 V – 60 Hz	220/380 V – 50 Hz	240/415 V – 50 Hz
Inductors	Number	5		
	Reactance	240/120/60/60/30 Ω	880/440/220/220/110 Ω	960/480/240/240/120 Ω
	Nominal Voltage	120 V – 60 Hz	220 V – 50 Hz	240 V – 50 Hz
	Accuracy	5%		
Toggle Switch	Number	5 - connected in series with each resistor		
Load at Nominal Voltage	Reactive Power	60 to 1170 vars	55 to 1045 vars	60 to 1040 vars
	Current	0.5 to 9.5 A	0.25 to 4.75 A	
	Number of Steps	19 of equal increment		
	Current Increment	0.5 A	0.25 A	
Physical Characteristics	Dimensions (H x W x D)	154 x 287 x 440 mm (6.1 x 11.3 x 17.3 in)		
	Net Weight	17.1 kg (37.6 lb)		

Model 8842-A – Rectifier and Filtering Capacitors		120/208 V – 60 Hz	220/380 V – 50 Hz	240/415 V – 50 Hz
Rectifier	Peak Increase Voltage	800 V	TBE	TBE
	Maximum Current	12 A	TBE	TBE
Capacitors (2)		210 μF - 450 V dc	TBE	TBE
Physical Characteristics	Dimensions (H x W x D)	154 x 287 x 440 mm (6.1 x 11.3 x 17.3 in)		
	Net Weight	TBE		

Model 8524 – Field Rheostat		120/208 V – 60 Hz	220/380 V – 50 Hz	240/415 V – 50 Hz
Resistance	Range	0 to 200 Ω	0 to 600 Ω	
	Power	225 W	225 W	
Physical Characteristics	Dimensions (H x W x D)	154 x 287 x 460 mm (6.1 x 11.3 x 18.1 in)		
	Net Weight	4.8 kg (10.6 lb)		
Model 8525 – Power Supply		**120/208 V – 60 Hz**	**220/380 V – 50 Hz**	**240/415 V – 50 Hz**
Input	Line Voltage	120/208 V – 60 Hz	220/380 V – 50 Hz	240/415 V – 50 Hz
	Line Current	15 A	10 A	
	Service Installation	3-phase, 5-wire, wye-connected including neutral and ground		
Outputs	Fixed AC, 3 Phases	120/208 V – 15 A	220/380 V – 10 A	240/415 V – 10 A
	Fixed AC, 1 Phase	120 V – 15 A	220 V – 10 A	240 V – 10 A
	Variable AC, 3 Phases	0 to 120/208 V – 15 A	0 to 220/380 V – 7 A	0 to 240/415 V – 7 A
	Fixed DC	120 V – 5 A	220 V – 3 A	240 V – 3 A
	Variable DC	0 to 120 V – 25 A	0 to 220 V – 12 A	0 to 240 V – 12 A
Power Cord	Length	3 m (10 ft)		
	Connector	120/208 V – 15 A NEMA L21 - 20	277/480 V – 15 A, NEMA L22 - 20	

Model 8952 – Connection Leads		
Lead Characteristics	Cross Section	2.5 mm² (3875 mil²)
	Strands per Lead	651
	Rated Current	32 A
	Rated Voltage	1000 V
	Contact Resistance	< 0.3 Ω
Number of 4-mm Leads	Yellow, 30 cm (12 in)	17
	Red, 60 cm (24 in)	15
	Blue, 90 cm (36 in)	8
Lead Holder		
Physical Characteristics	Dimensions (H x W x D)	90 x 315 x 80 mm (3.5 x 12.4 x 3.1 in)
	Net Weight	1.5 kg (3.3 lb)

Appendix B: Fluke Three Phase Power Quality Analyzer Specifications

Inputs	**Number:**	4 voltage and current (3 phases + neutral)
	Maximum voltage:	1000 Vrms (6 kV peak)
	Maximum sampling speed:	200 kS/s on each channel simultaneously
Volt/Amps/Hertz	**Vrms (AC + DC)**	
	Measurement range:	1 ... 1000 V
	Accuracy:	0.1% of Vnom
	Vpeak	
	Measurement range:	1 ... 1400 V
	Accuracy:	5% of Vnom
	Crest factor, voltage	
	Measurement range:	1.0 ... > 2.8
	Accuracy:	±5%
	Arms (AC + DC)	
	Measurement range:	0 ... 20 kA
	Accuracy:	±0.5% ± 5 counts
	Apeak	
	Measurement range:	1.4x rms value
	Accuracy:	5%
	Crest factor, A	
	Measurement range:	1 ... 10
	Accuracy:	±5%
	Hz 50 Hz nominal	
	Measurement range:	40 ... 70 Hz
	Accuracy:	±0.01 Hz
Harmonics	**Harmonic (interharmonic) (n)**	
	Measurement range:	DC, 1..50; (Off, 1..49) measured according to IEC 61000-4-7
	Vrms	
	Measurement range:	0.0 ... 1000 V
	Accuracy:	±0.05% of nominal voltage
	Arms	
	Measurement range:	0.0 ... 4000 mV x clamp scaling
	Accuracy:	±5% ± 5 counts
	Watts	
	Measurement range:	Depends on clamp scaling and voltage
	Accuracy:	±5% ± n x 2% or reading, ± 10 counts
	DC voltage	
	Measurement range:	0.0 ... 1000 V
	Accuracy:	±0.2% of nominal voltage
	THD	
	Measurement range:	0.0 ... 100.0%
	Accuracy:	±2.5% V and A (± 5% Watt)
	Hz	
	Measurement range:	0 ... 3500 Hz
	Accuracy:	± 1 Hz
	Phase angle	
	Measurement range:	-360° ... +360°
	Accuracy:	± n x 1.5°
Power and energy	**Watt, VA, VAR**	
	Measurement range:	1.0 ... 20.00 MVA[1]
	Accuracy:	±1% ± counts
	kWh, kVAh, kVARh	
	Measurement range:	00.00 ...200.0 GVAh[1]
	Accuracy:	± 1.5% ± 10 counts
	Power Factor/ Cos Φ / DPF	
	Measurement range:	0...1
	Accuracy:	± 0.03

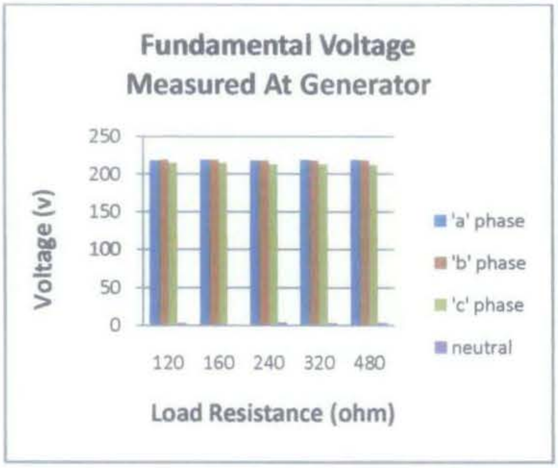
Unbalance	**Volts** **Measurement range:** 0.0 ... 5.0% **Accuracy:** ±0.5% **Current** **Measurement range:** 0.0 ... 20% **Accuracy:** ± 1%
Logging	**Sampling:** 5 readings/sec continuous sampling per channel **Readings:** User selectable up to 100 readings on 3 phases and neutral simultaneously **Averaging:** 2hr down to 0.5s user selectable **Memory:** User selectable up to 7MB of shared memory **Recording time:** User selectable, depends on selected number of readings **Zoom:** Yes
Autotrend recording	**Sampling:** 5 readings/sec continuous sampling per channel **Memory:** 1800 min, max and avg points for each reading **Recording time:** Up to 450 days **Zoom:** Up to 12x horizontal zoom
Memory	**Screens & data:** 50, shared memory divided between logging, screens and data sets
Notes	[1] Depending on clamp scaling [2] Value is measured over 1 cycle, commencing at a fundamental zero crossing, and refreshed each half-cycle

Environmental Specifications	
Operating Temperature	0 °C to +50 °C

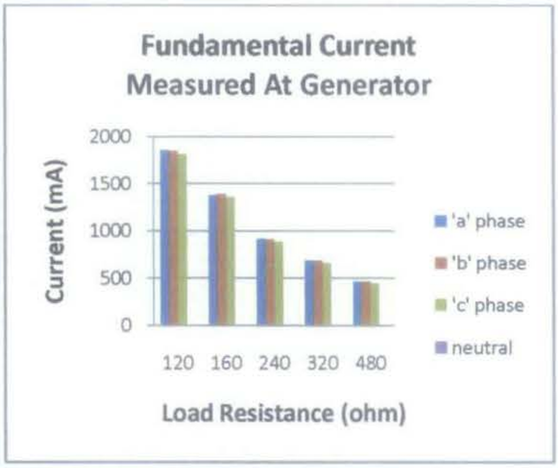
Safety Specifications	
Safety	EN61010-1 (2nd edition) pollution degree 2; 1000 V CAT III / 600 V CAT IV ANSI/ISA S82.01

Mechanical & General Specifications	
Size	256 x 169 x 64 mm
Weight	2 kg
Battery Life	**Rechargeable NiMH pack (installed):** >7 hours **Battery charging time:** 4 hours typical
Shock & Vibration	**Shock:** 30 g **Vibration:** 3 g according to MIL-PRF-28800F Class 2
Case	Rugged, shock proof with integrated protective holster, IP51 (drip and dust proof)
Warranty	3 years

Appendix C: Single Generator Connected To Resistive Load



Graph of Fundamental Voltage Measured At Generator When Single Generator Connected To Various Resistive Load



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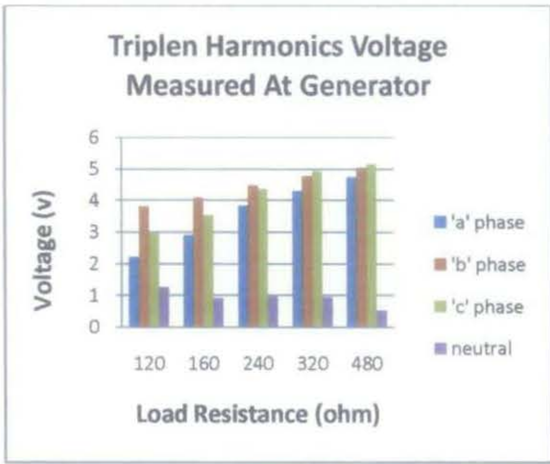
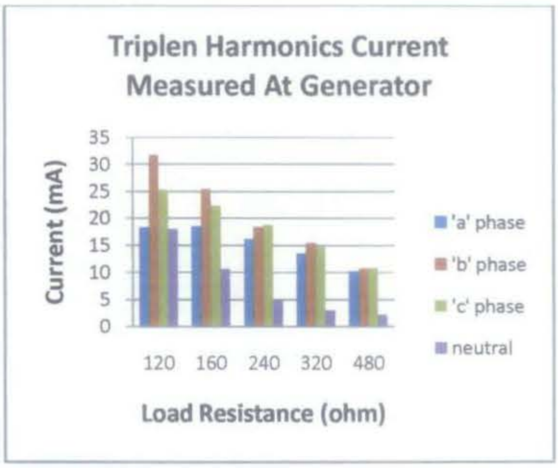
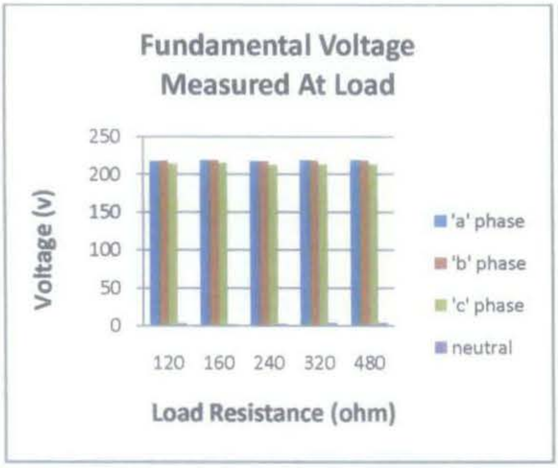


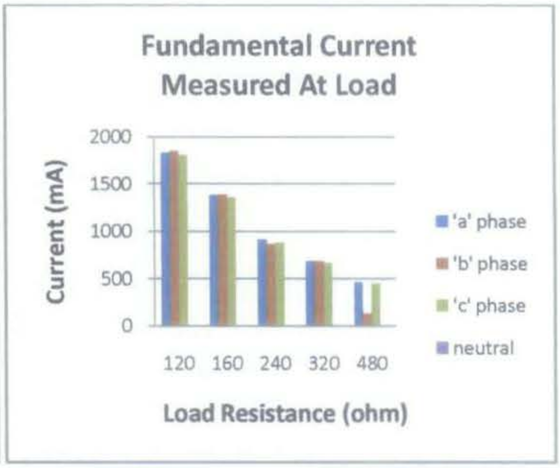
Graph of Triplen Harmonics Voltage Measured At Generator When Single Generator Connected To Various Resistive Load



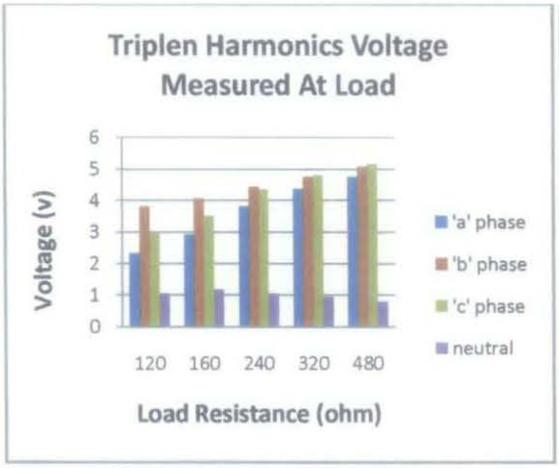
Graph of Triplen Harmonics Current Measured At Generator When Single Generator Connected To Various Resistive Loads



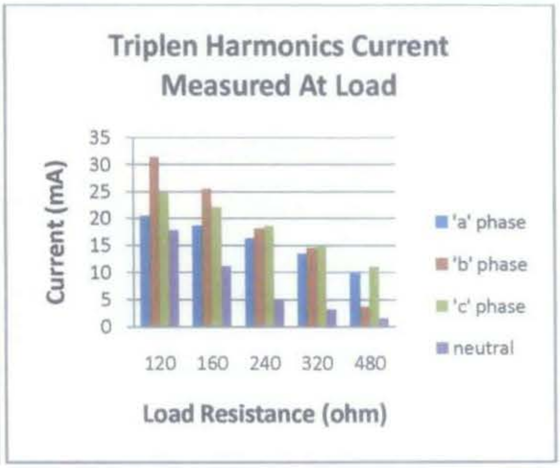
Graph of Fundamental Voltage Measured At Load When Single Generator Connected To Various Resistive Load



Graph of Fundamental Current Measured At Load When Single Generator Connected To Various Resistive Load

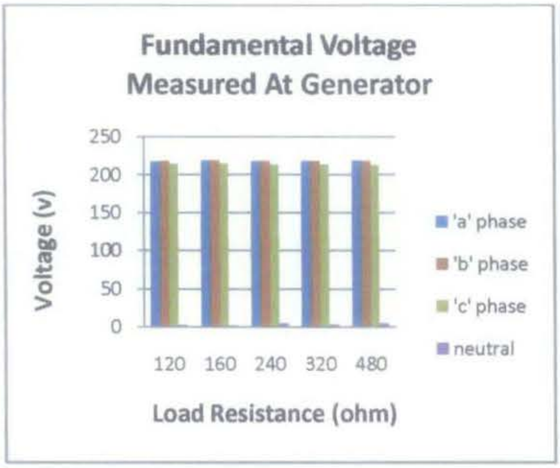


Graph of Triplen Harmonics Voltage Measured At Load When Single Generator Connected To Various Resistive Load

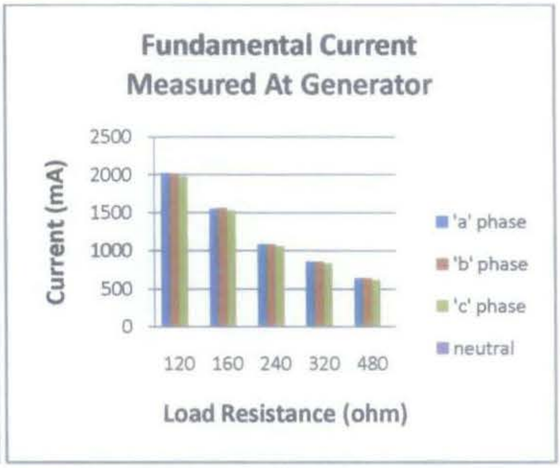


Graph of Triplen Harmonics Current Measured At Load When Single Generator Connected To Various Resistive Loads

Appendix D: Single Generator Connected To Resistive Load with Full Bridge Rectifier



Graph of Fundamental Voltage Measured At Generator When Single Generator Connected To Various Resistive Load with Full Bridge Rectifier



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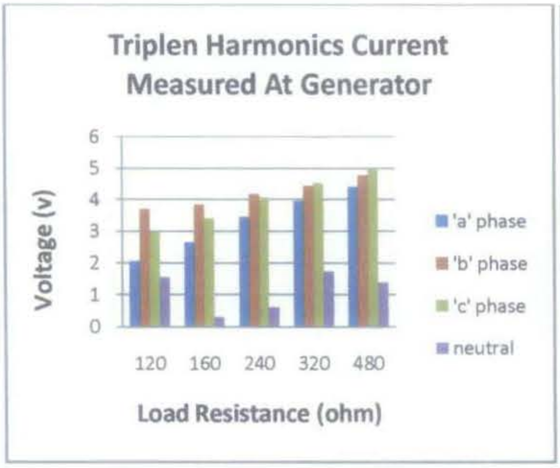
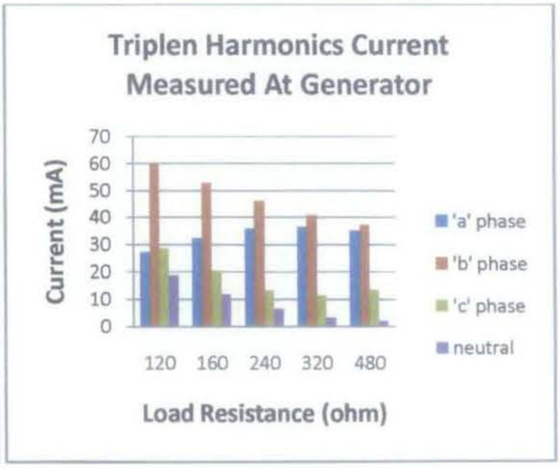
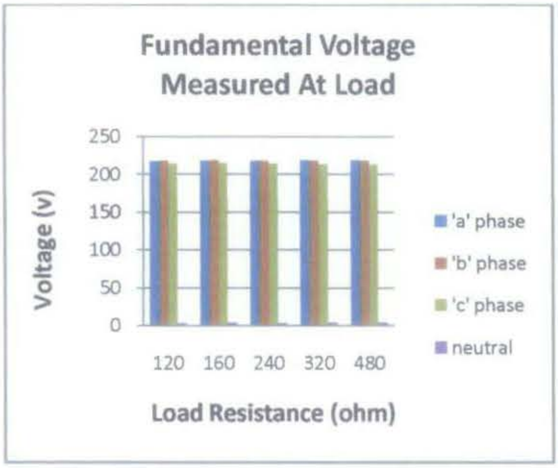


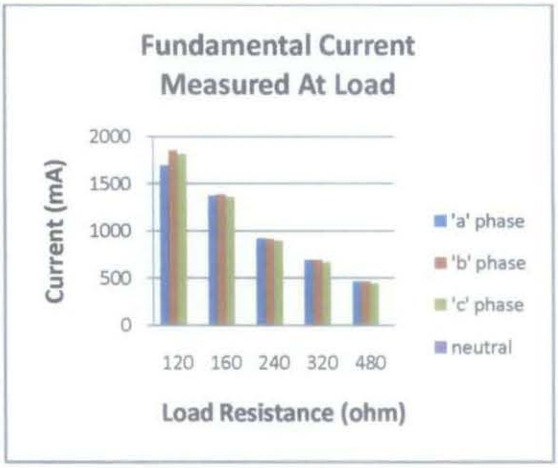
Graph of Triplen Harmonics Voltage Measured At Generator When Single Generator Connected To Various Resistive Load with Full Bridge Rectifier



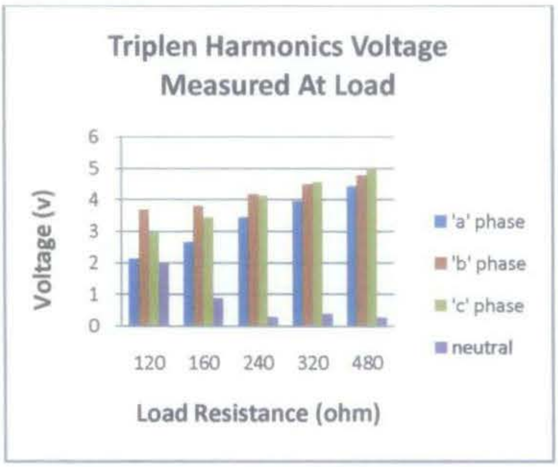
Graph of Triplen Harmonics Current Measured At Generator When Single Generator Connected To Various Resistive Loads with Full Bridge Rectifier



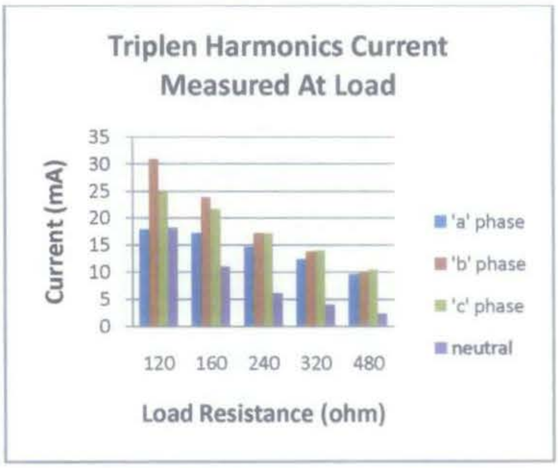
Graph of Fundamental Voltage Measured At Load When Single Generator Connected To Various Resistive Load with Full Bridge Rectifier



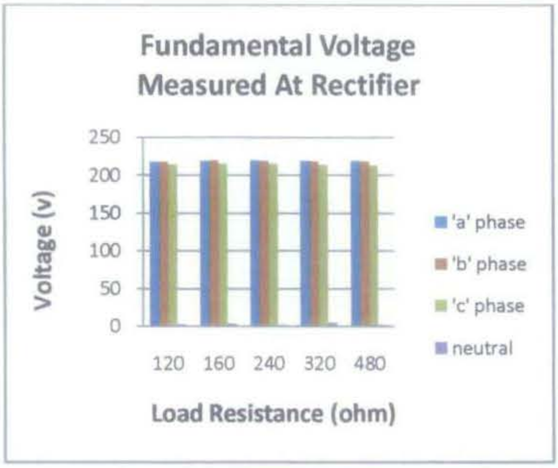
Graph of Fundamental Current Measured At Load When Single Generator Connected To Various Resistive Load with Full Bridge Rectifier



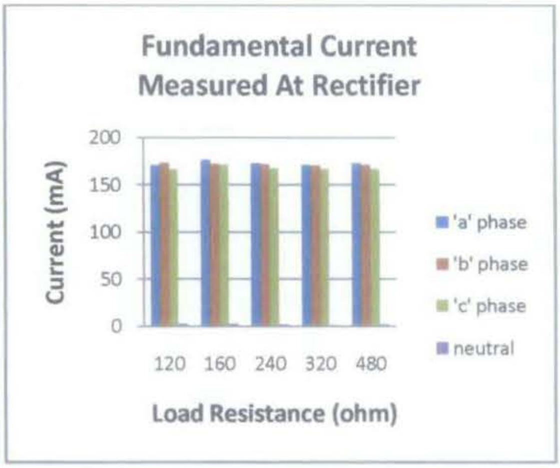
Graph of Triplen Harmonics Voltage Measured At Load When Single Generator Connected To Various Resistive Load with Full Bridge Rectifier



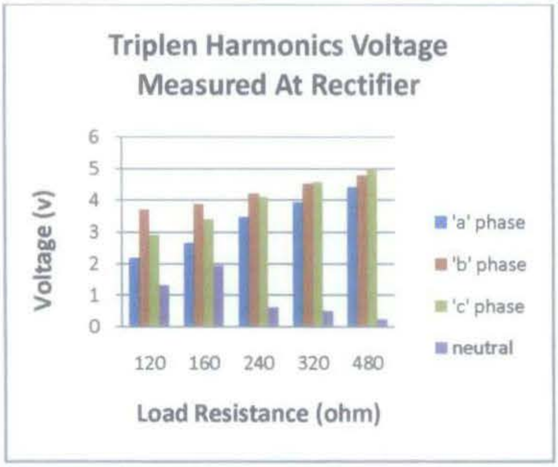
Graph of Triplen Harmonics Current Measured At Load When Single Generator Connected To Various Resistive Loads with Full Bridge Rectifier



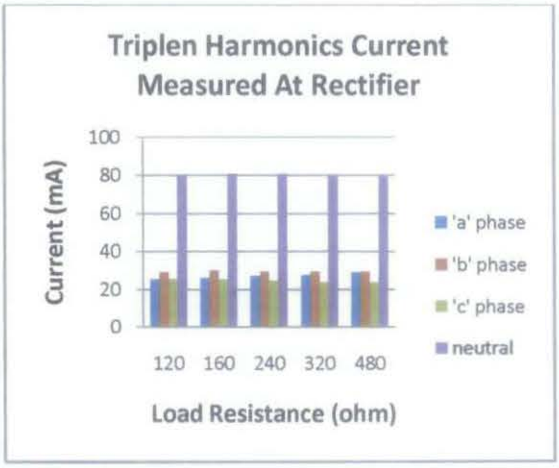
Graph of Fundamental Voltage Measured At Rectifier When Single Generator Connected To Various Resistive Load with Full Bridge Rectifier



Graph of Fundamental Current Measured At Rectifier When Single Generator Connected To Various Resistive Load with Full Bridge Rectifier

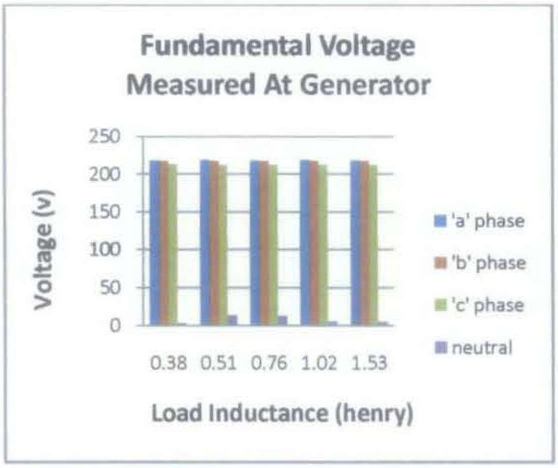


Graph of Triplen Harmonics Voltage Measured At Rectifier When Single Generator Connected To Various Resistive Load with Full Bridge Rectifier

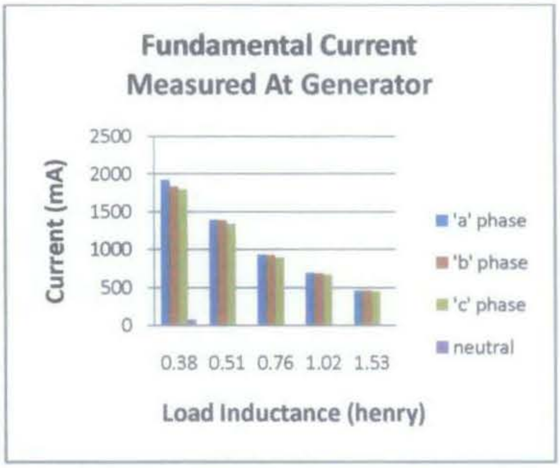


Graph of Triplen Harmonics Current Measured At Rectifier When Single Generator Connected To Various Resistive Loads with Full Bridge Rectifier

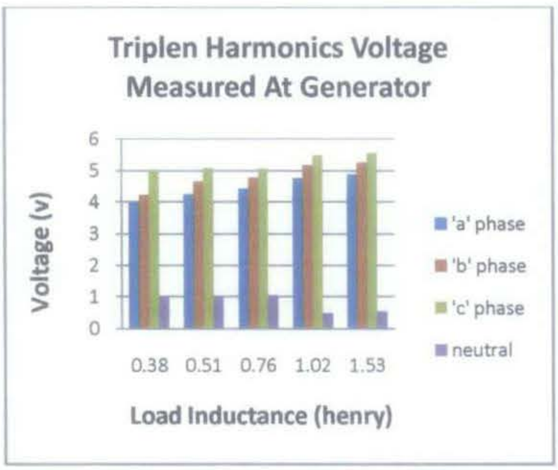
Appendix E: Single Generator Connected To Inductive Load



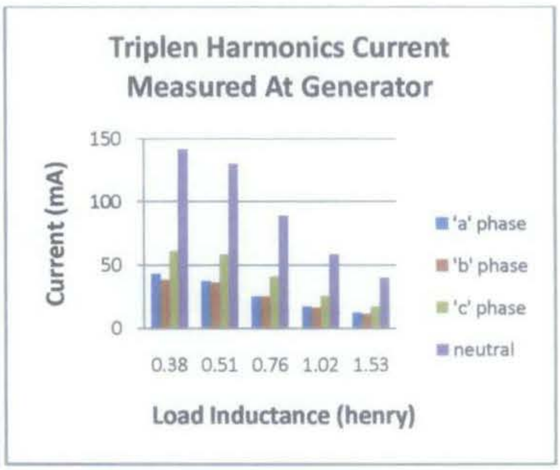
Graph of Fundamental Voltage Measured At Generator When Single Generator Connected To Various Inductive Load



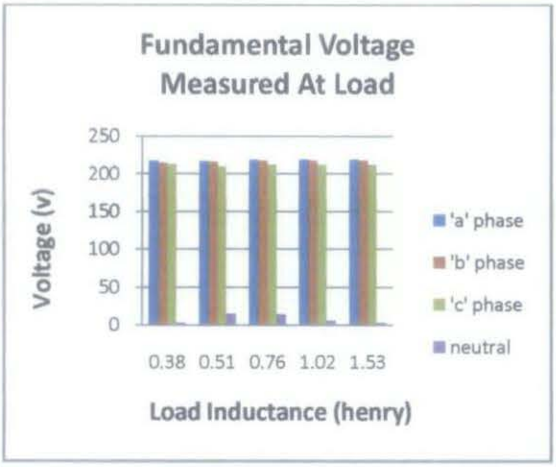
Graph of Fundamental Current Measured At Generator When Single Generator Connected To Various Inductive Load



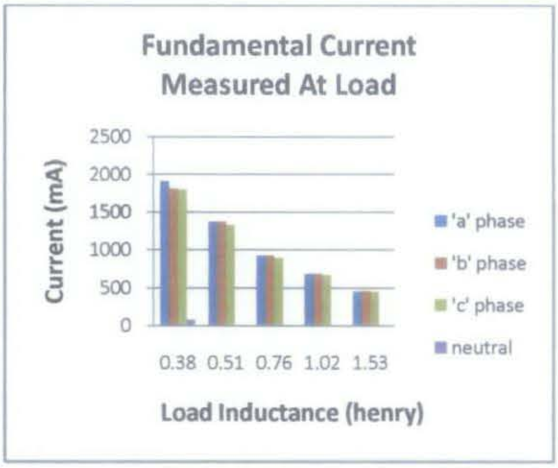
Graph of Triplen Harmonics Voltage Measured At Generator When Single Generator Connected To Various Inductive Load



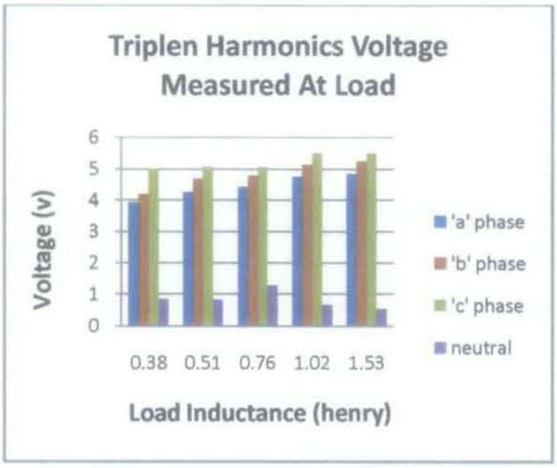
Graph of Triplen Harmonics Current Measured At Generator When Single Generator Connected To Various Inductive Loads



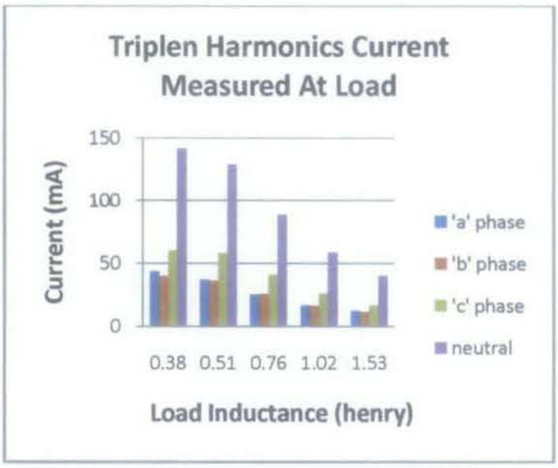
Graph of Fundamental Voltage Measured At Load When Single Generator Connected To Various Inductive Load



Graph of Fundamental Current Measured At Load When Single Generator Connected To Various Inductive Load

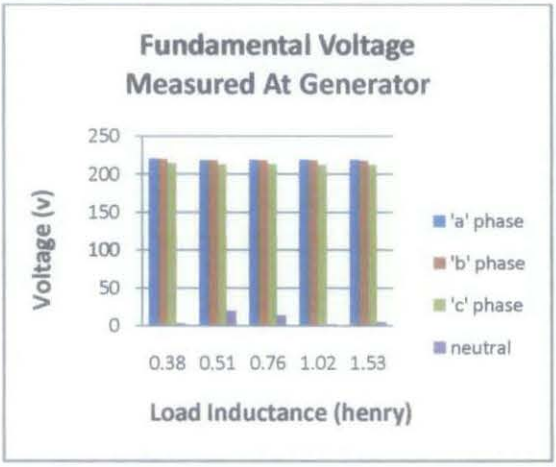


Graph of Triplen Harmonics Voltage Measured At Load When Single Generator Connected To Various Inductive Load

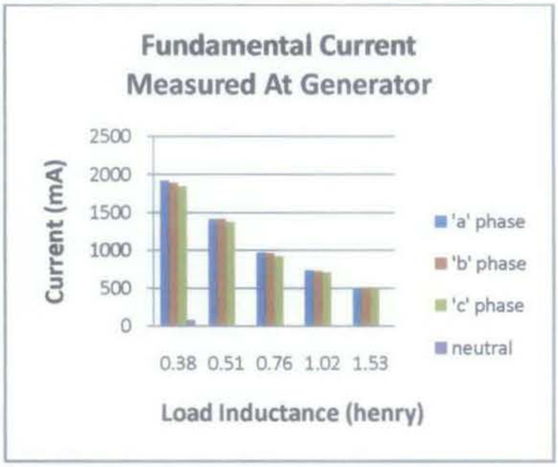


Graph of Triplen Harmonics Current Measured At Load When Single Generator Connected To Various Inductive Loads

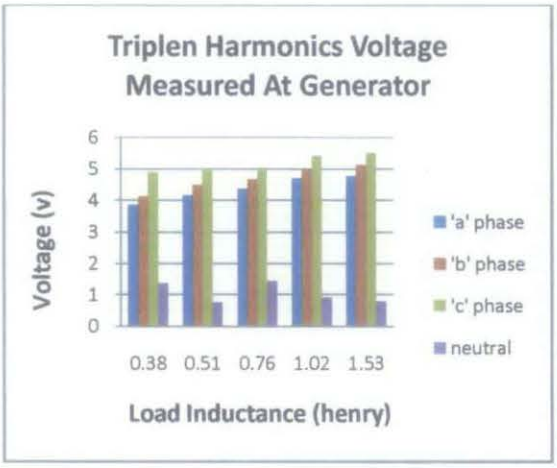
Appendix F: Single Generator Connected To Inductive Load with Full Bridge Rectifier



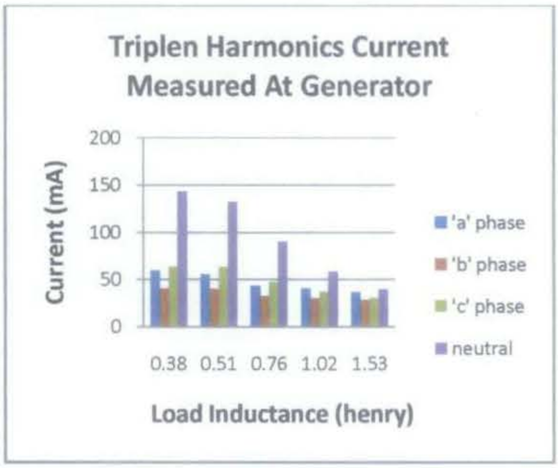
Graph of Fundamental Voltage Measured At Generator When Single Generator Connected To Various Inductive Load with Full Bridge Rectifier



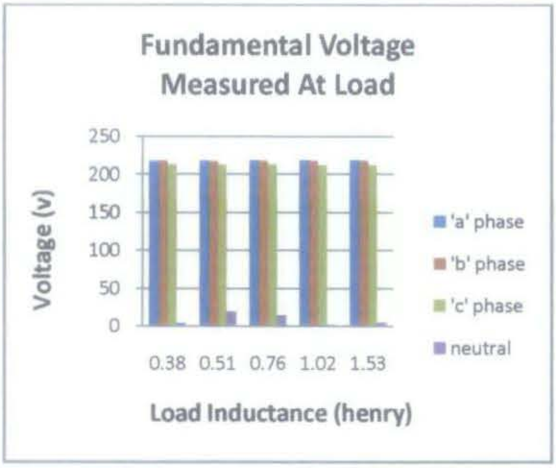
Graph of Fundamental Current Measured At Generator When Single Generator Connected To Various Inductive Load with Full Bridge Rectifier



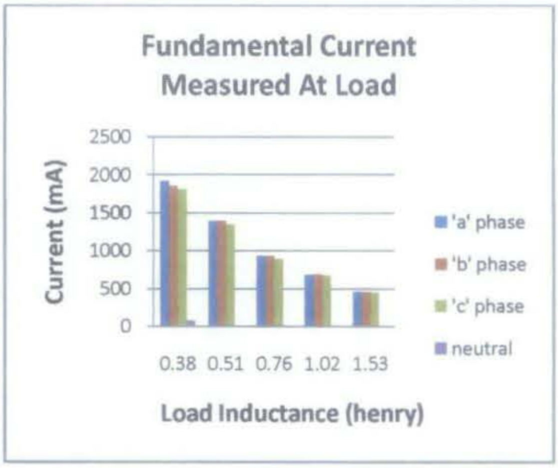
Graph of Triplen Harmonics Voltage Measured At Generator When Single Generator Connected To Various Inductive Load with Full Bridge Rectifier



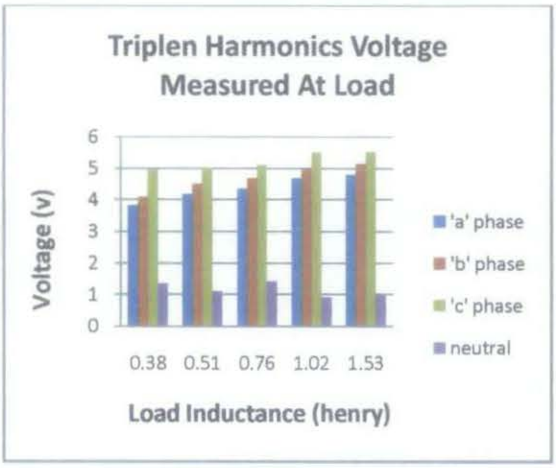
Graph of Triplen Harmonics Current Measured At Generator When Single Generator Connected To Various Inductive Loads with Full Bridge Rectifier



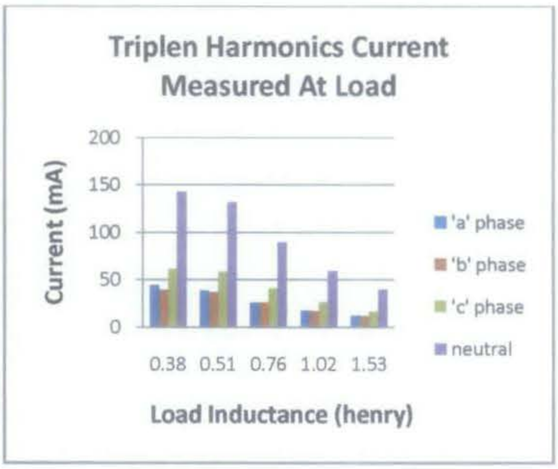
Graph of Fundamental Voltage Measured At Load When Single Generator Connected To Various Inductive Load with Full Bridge Rectifier



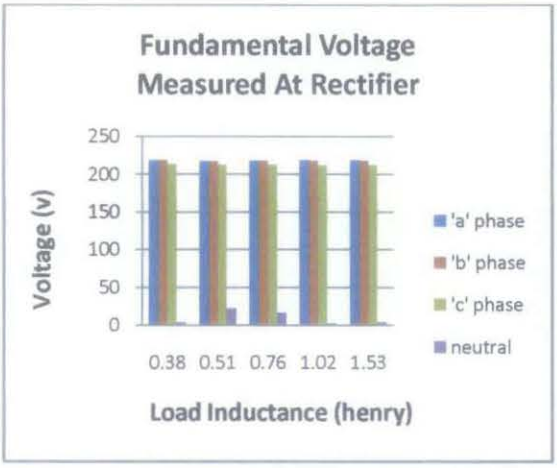
Graph of Fundamental Current Measured At Load When Single Generator Connected To Various Inductive Load with Full Bridge Rectifier



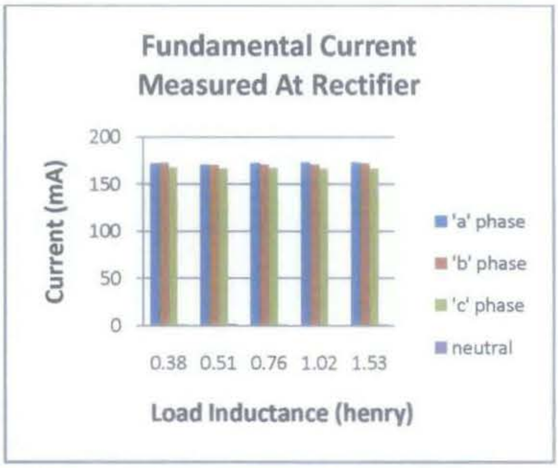
Graph of Triplen Harmonics Voltage Measured At Load When Single Generator Connected To Various Inductive Load with Full Bridge Rectifier



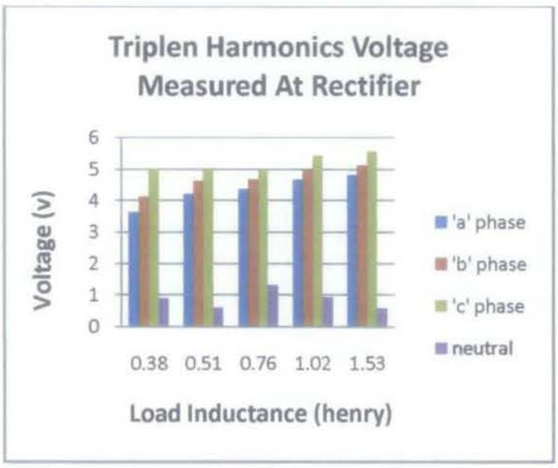
Graph of Triplen Harmonics Current Measured At Load When Single Generator Connected To Various Inductive Loads with Full Bridge Rectifier



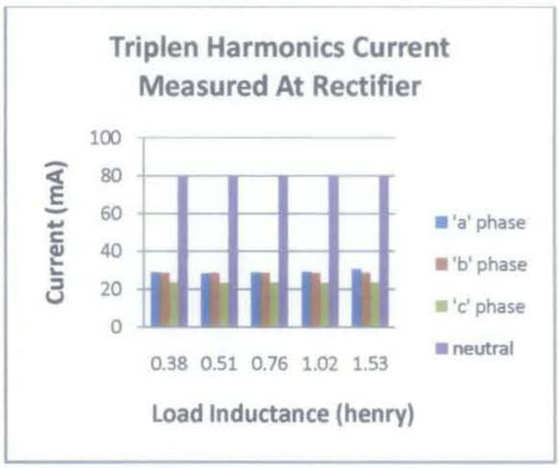
Graph of Fundamental Voltage Measured At Rectifier When Single Generator Connected To Various Inductive Load with Full Bridge Rectifier



Graph of Fundamental Current Measured At Rectifier When Single Generator Connected To Various Inductive Load with Full Bridge Rectifier

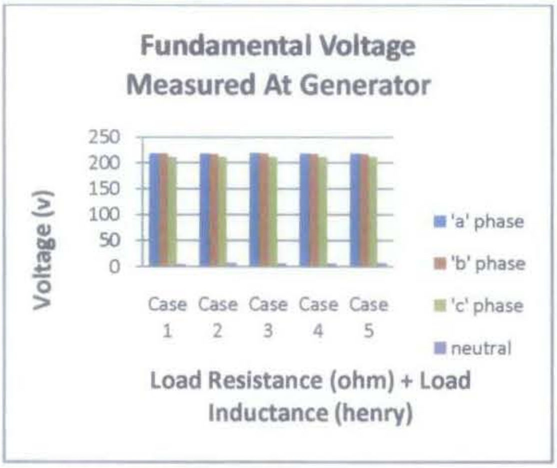


Graph of Triplen Harmonics Voltage Measured At Rectifier When Single Generator Connected To Various Inductive Load with Full Bridge Rectifier

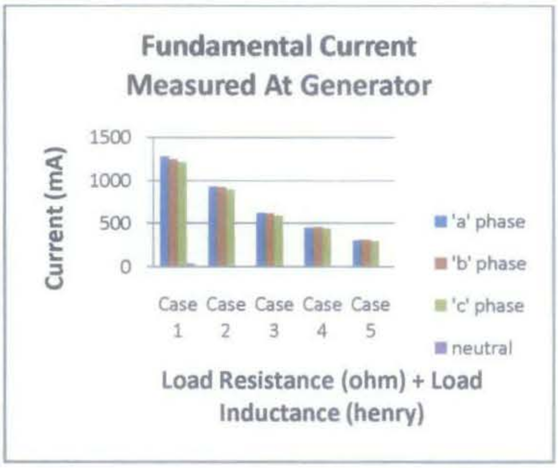


Graph of Triplen Harmonics Current Measured At Rectifier When Single Generator Connected To Various Inductive Loads with Full Bridge Rectifier

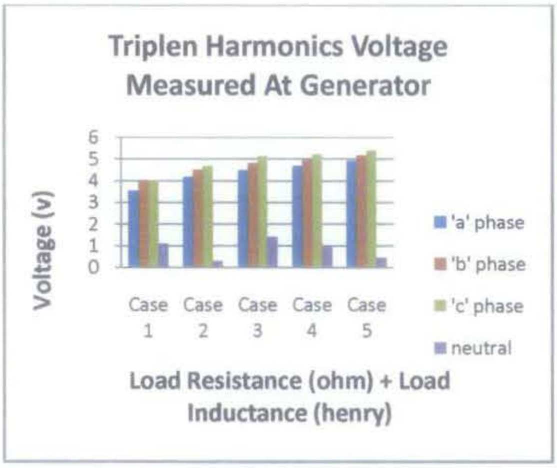
Appendix G: Single Generator Connected To Resistive and Inductive Load



Graph of Fundamental Voltage Measured At Generator When Single Generator Connected To Various Resistive and Inductive Load



Graph of Fundamental Current Measured At Generator When Single Generator Connected To Various Resistive and Inductive Load



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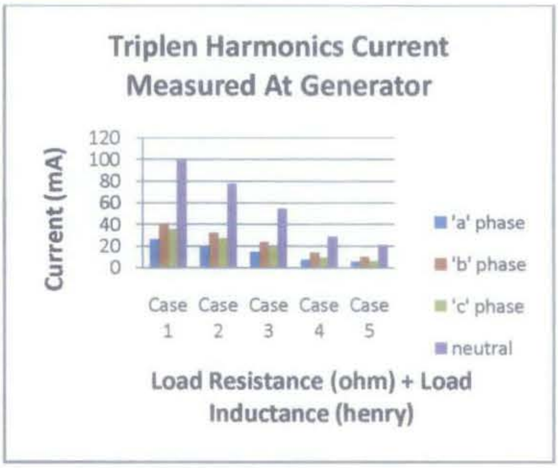
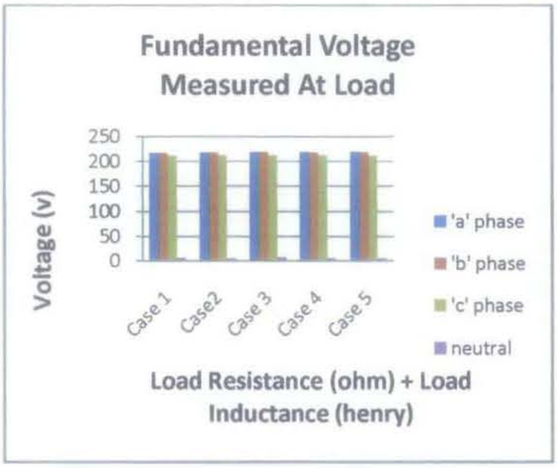
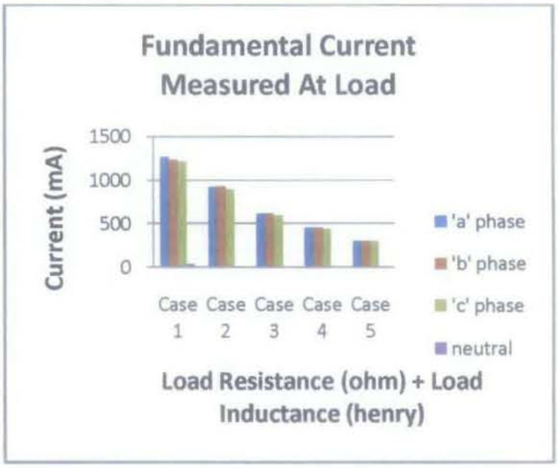


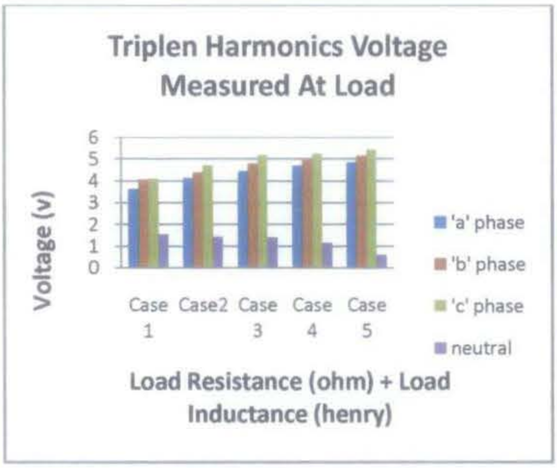
Graph of Triplen Harmonics Current Measured At Generator When Single Generator Connected To Various Resistive and Inductive Loads



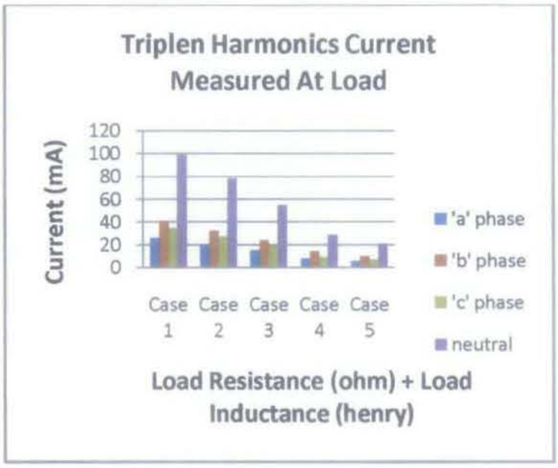
Graph of Fundamental Voltage Measured At Load When Single Generator Connected To Various Resistive and Inductive Load



Graph of Fundamental Current Measured At Load When Single Generator Connected To Various Resistive and Inductive Load

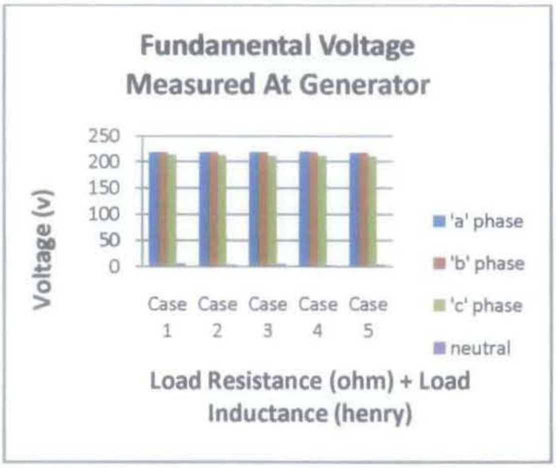


Graph of Triplen Harmonics Voltage Measured At Load When Single Generator Connected To Various Resistive and Inductive Load

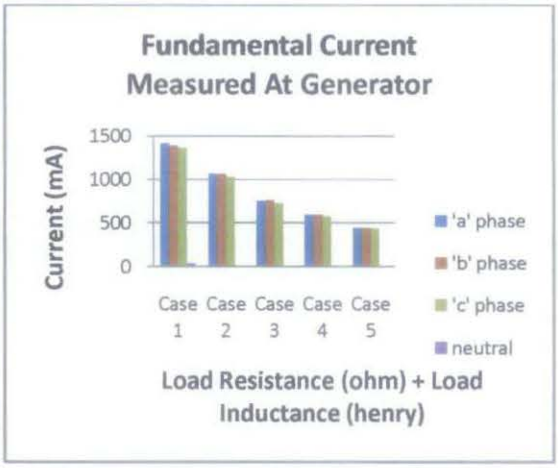


Graph of Triplen Harmonics Current Measured At Load When Single Generator Connected To Various Resistive and Inductive Loads

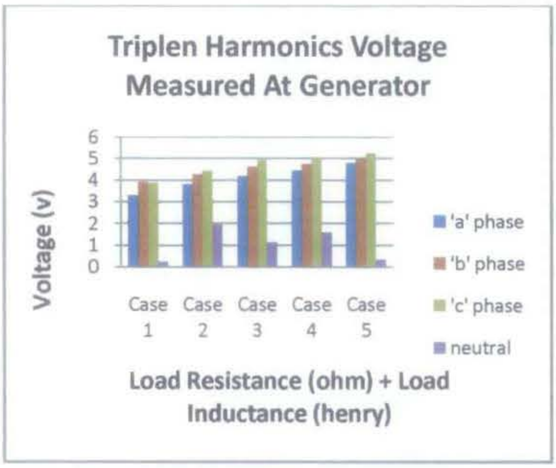
Appendix H: Single Generator Connected To Resistive and Inductive Load with Rectifier



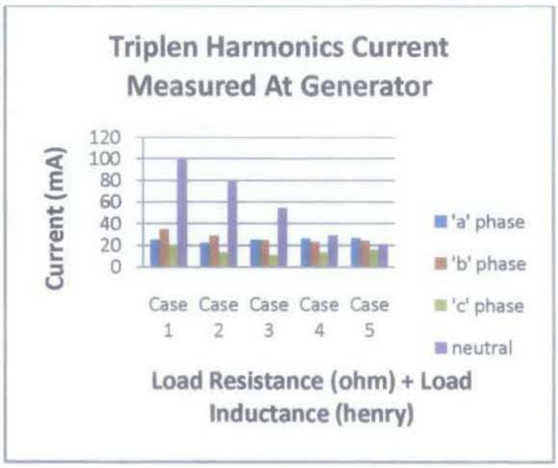
Graph of Fundamental Voltage Measured At Generator When Single Generator Connected To Various Resistive and Inductive Load with Full Bridge Rectifier



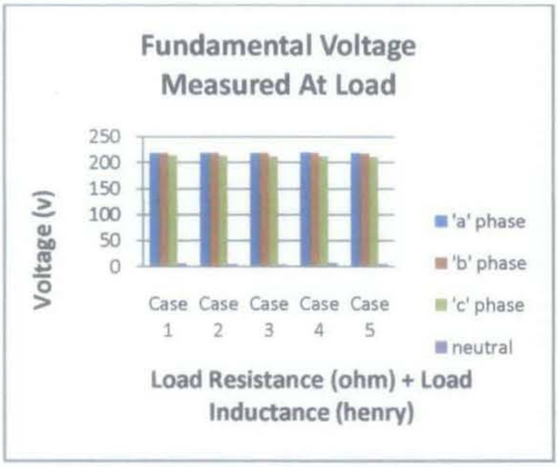
Graph of Fundamental Current Measured At Generator When Single Generator Connected To Various Resistive and Inductive Load with Full Bridge Rectifier



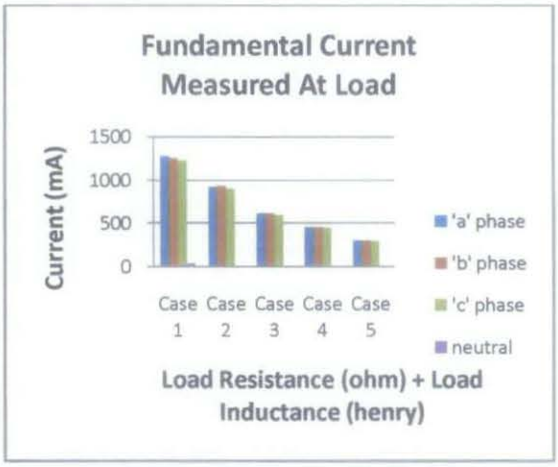
Graph of Triplen Harmonics Voltage Measured At Generator When Single Generator Connected To Various Resistive and Inductive Load with Full Bridge Rectifier



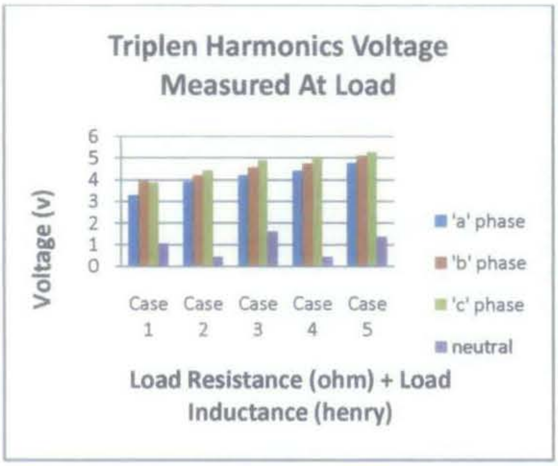
Graph of Triplen Harmonics Current Measured At Generator When Single Generator Connected To Various Resistive and Inductive Loads with Full Bridge Rectifier



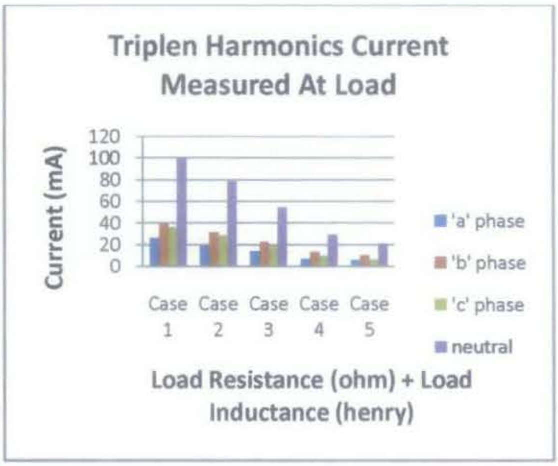
Graph of Fundamental Voltage Measured At Load When Single Generator Connected To Various Resistive and Inductive Load with Full Bridge Rectifier



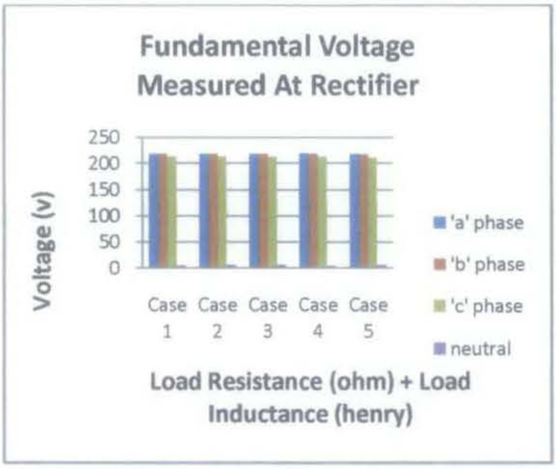
Graph of Fundamental Current Measured At Load When Single Generator Connected To Various Resistive and Inductive Load with Full Bridge Rectifier



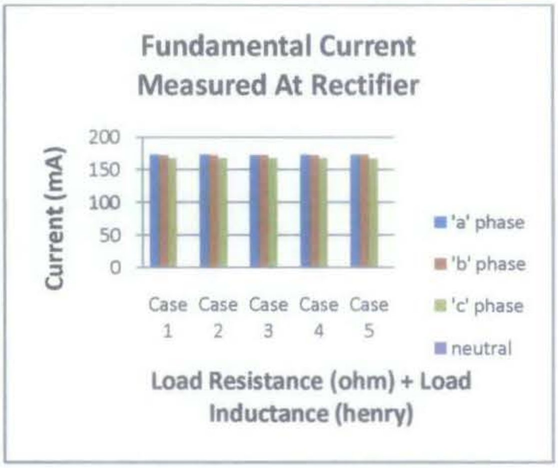
Graph of Triplen Harmonics Voltage Measured At Load When Single Generator Connected To Various Resistive and Inductive Load with Full Bridge Rectifier



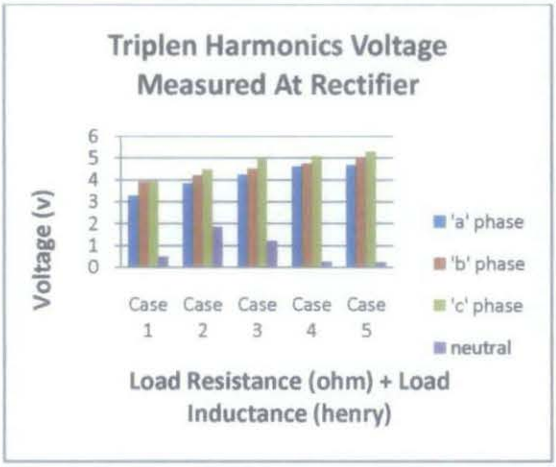
Graph of Triplen Harmonics Current Measured At Load When Single Generator Connected To Various Resistive and Inductive Loads with Full Bridge Rectifier



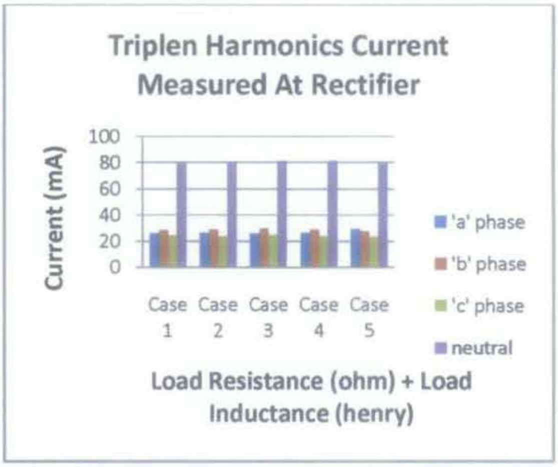
Graph of Fundamental Voltage Measured At Rectifier When Single Generator Connected To Various Resistive and Inductive Load with Full Bridge Rectifier



Graph of Fundamental Current Measured At Rectifier When Single Generator Connected To Various Resistive and Inductive Load with Full Bridge Rectifier



Graph of Triplen Harmonics Voltage Measured At Rectifier When Single Generator Connected To Various Resistive and Inductive Load with Full Bridge Rectifier



Graph of Triplen Harmonics Current Measured At Rectifier When Single Generator Connected To Various Resistive and Inductive Loads with Full Bridge Rectifier